Dark Matter in Light of the Results from ATIC, PAMELA, and WMAP

Lisa Goodenough CCPP NYU

Fermilab
February 16th, 2009

work with I. Cholis, G. Dobler, D. Finkbeiner, D. Hooper, M. Simet, and N. Weiner
in papers arXiv:0811.3641, 0810.5344, 0809.1683, 0802.2922

Outline

- *Brief* Notes on Dark Matter
- $e^+ e^-$ excesses in ATIC and PAMELA and their implications for DM theories
- WMAP Haze
- Implications of these signals for Fermi/GLAST

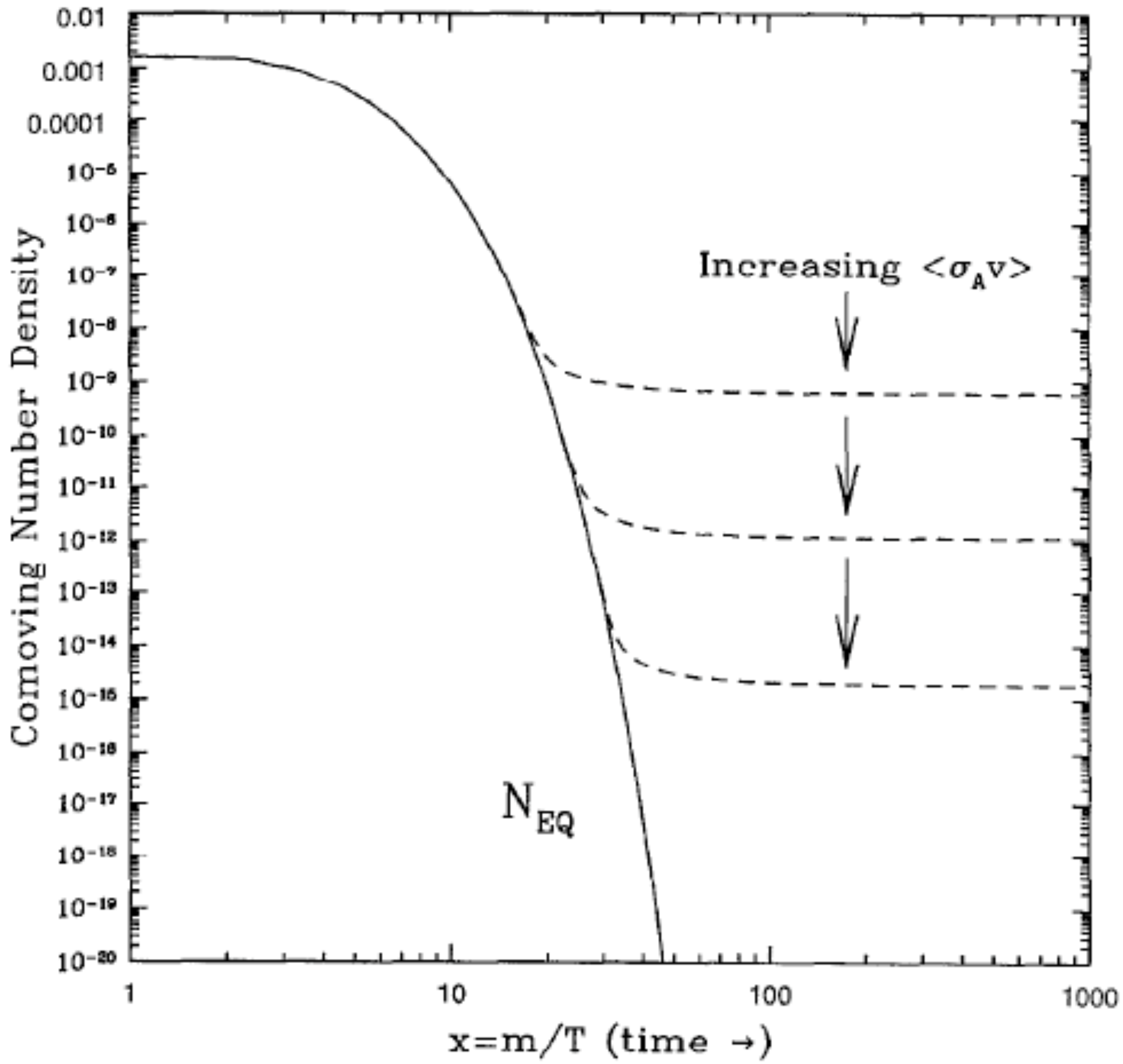
Dark Matter

WMAP 5-year
Type 1a supernovae
Baryon Acoustic Oscillations

$$\Omega_m h^2 = 0.1358^{+0.0037}_{-0.0036}$$

$$\Omega_b h^2 = 0.02267^{+0.00058}_{-0.00059}$$

$$\Omega_{DM} h^2 = 0.1131^{+0.0037}_{-0.0036}$$



Jungman, Kamionkowski and Greist

relic abundance for thermal freeze-out:

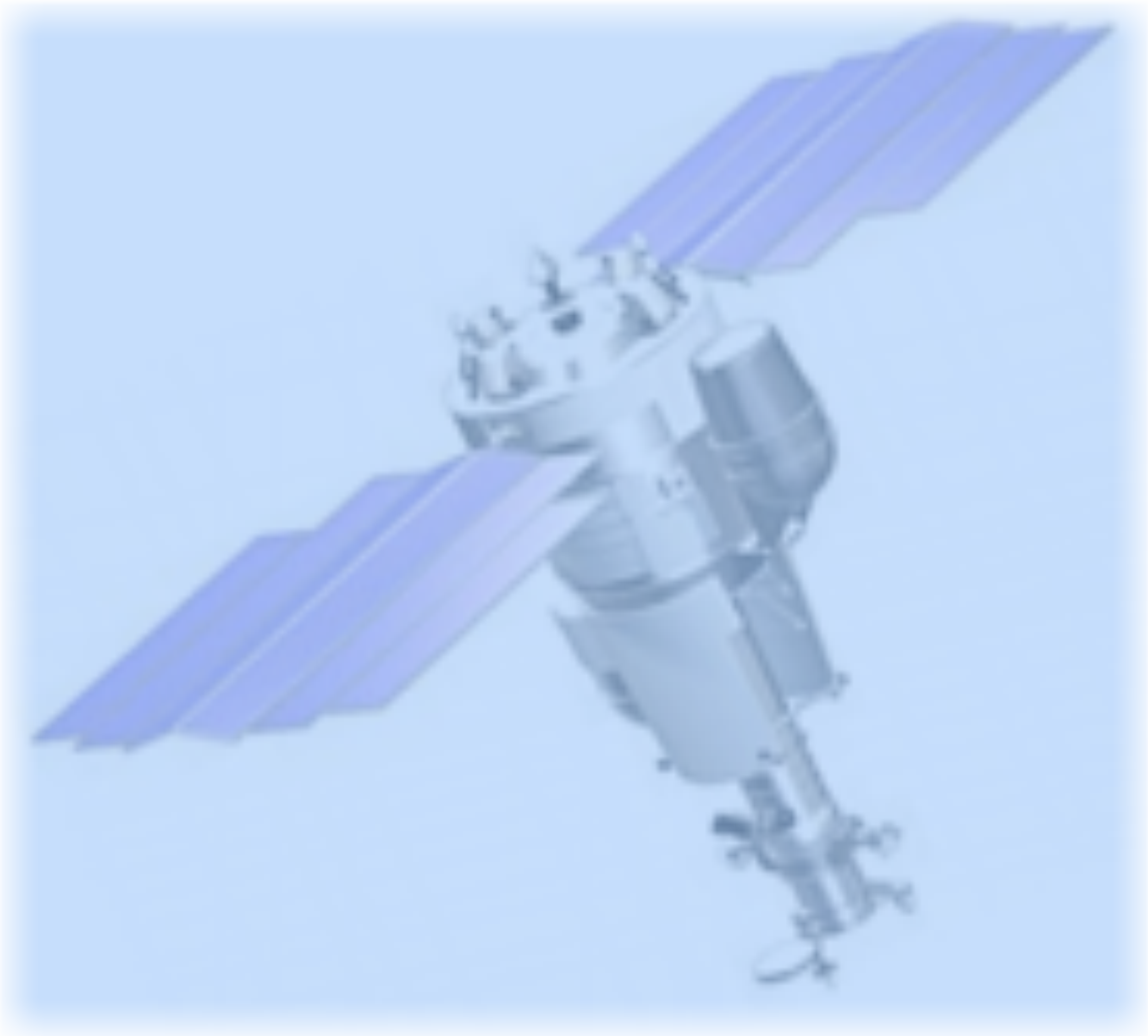
$$\Omega h^2 = 0.10 \; \frac{3\times 10^{-26}\ \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_{ann} |v| \rangle}$$

a particle with a weak-scale annihilation cross-section would have the correct relic abundance

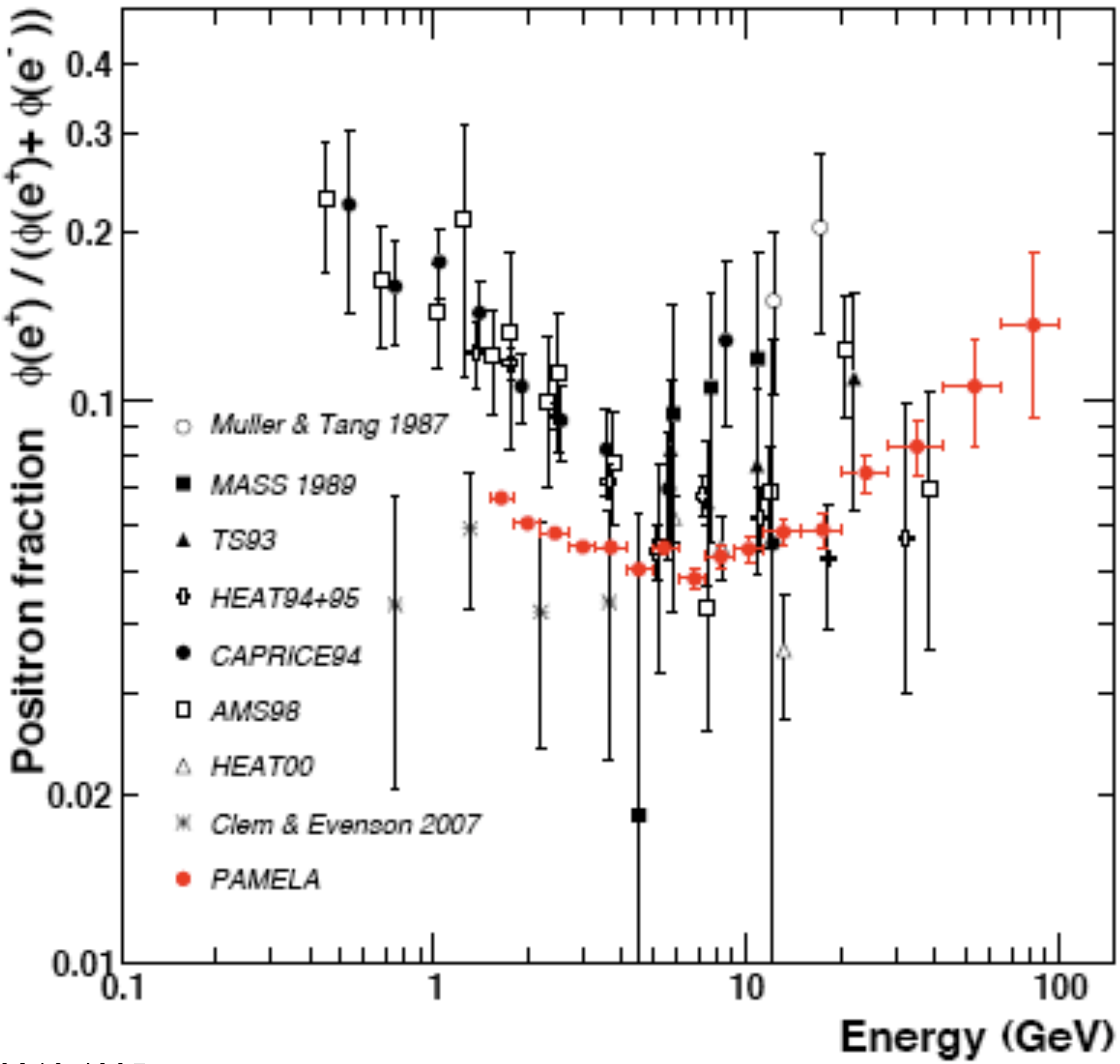
PAMELA

a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

- Satellite experiment launched in 2006
- Primary goal is to study the antimatter component of CRs, specifically to measure spectra of antiprotons and positrons
- Core of the instrument is a magnetic spectrometer that allows identification of positively and negatively charged particles



PAMELA Positron Fraction $\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$



Adriani *et al.* arXiv:0810.4995

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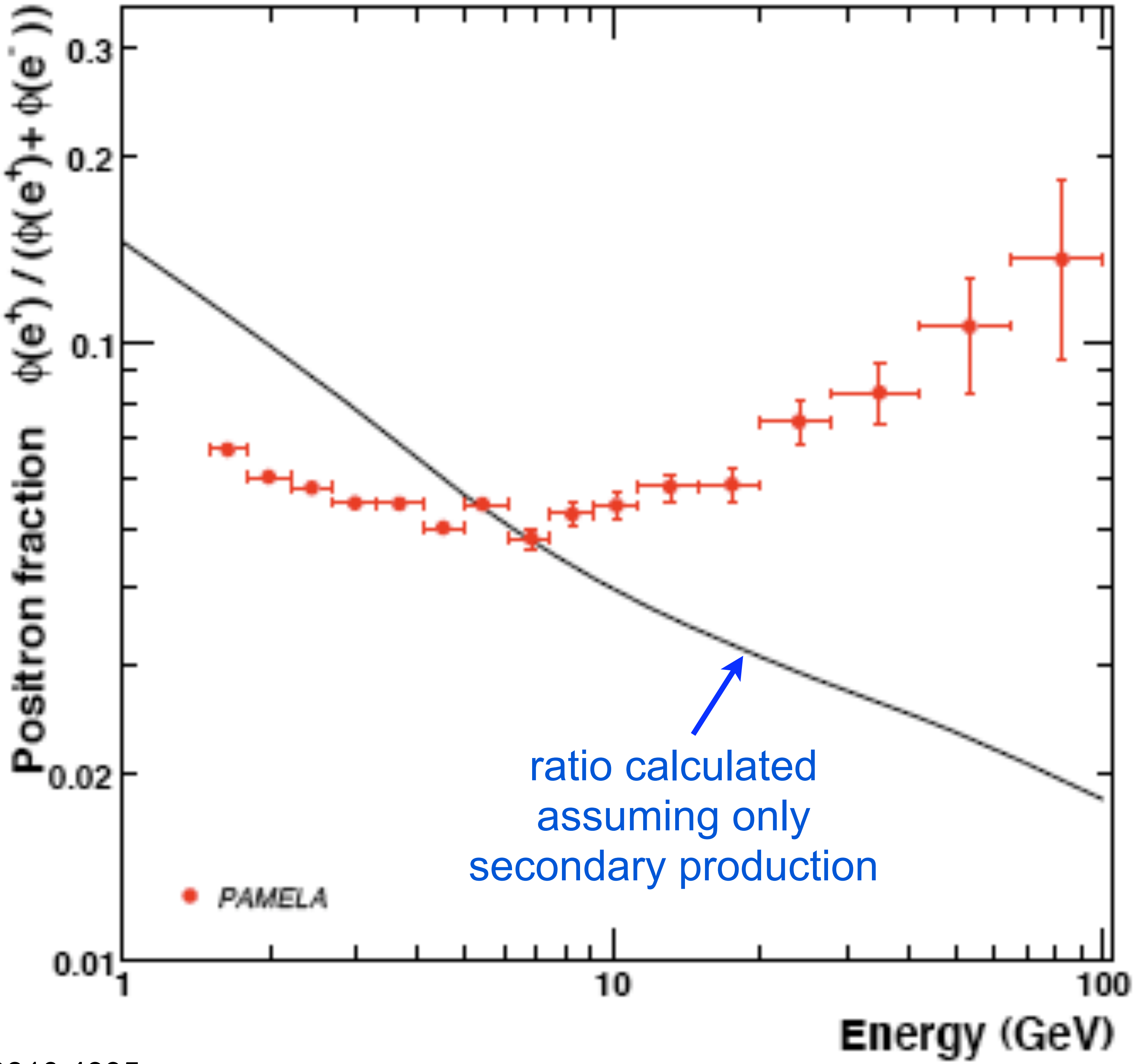

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ATIC

Advanced Thin Ionization Calorimeter

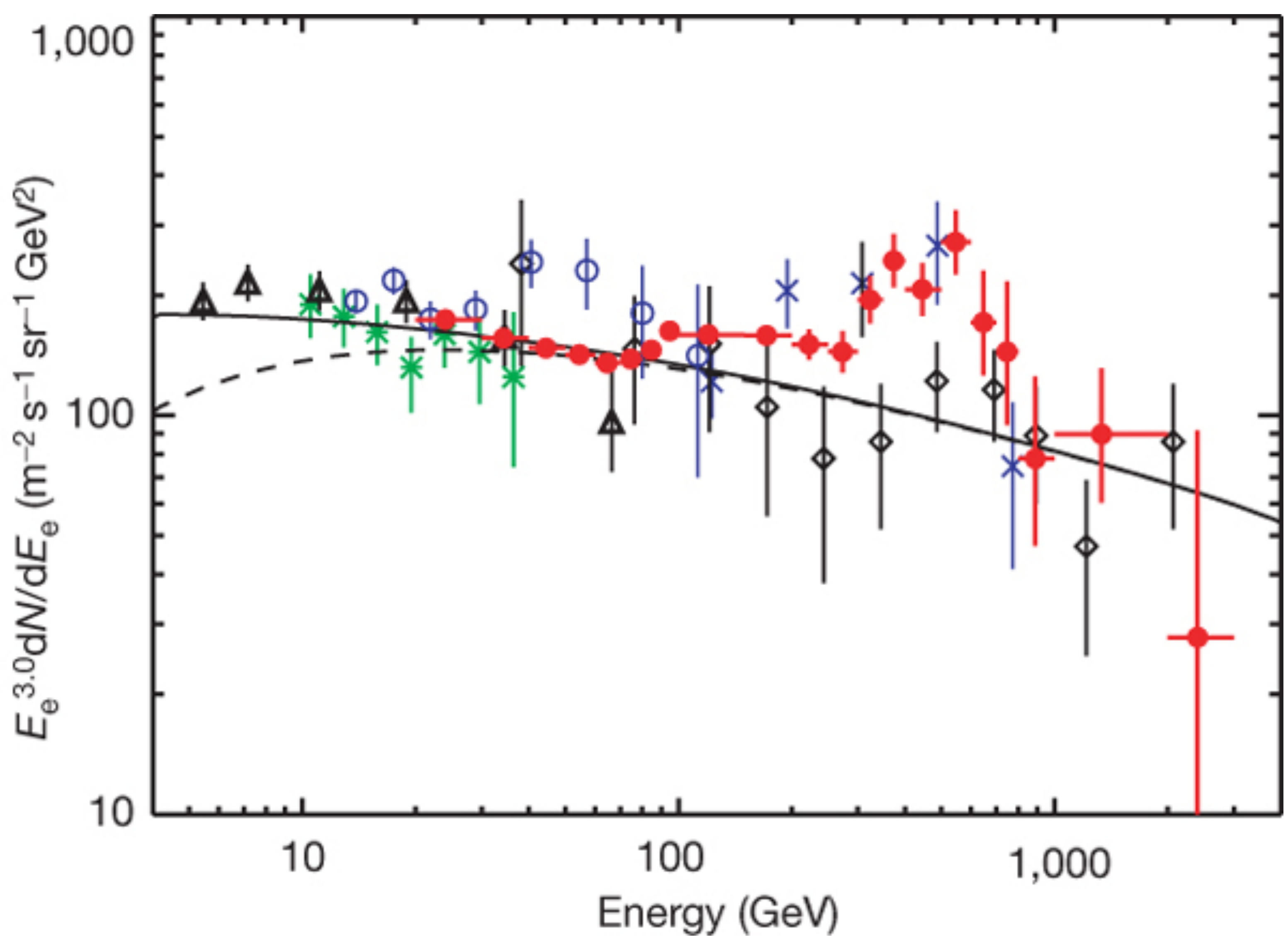
- Balloon experiment that collected data for five weeks in 2000 and 2003 and two weeks in 2007

- Measures total electronic flux ($e^+ + e^-$) in the energy range ~ 20-2400 GeV

- Can’t differentiate between electrons and positrons

ATIC

Electron Spectrum ($e^+ + e^-$)

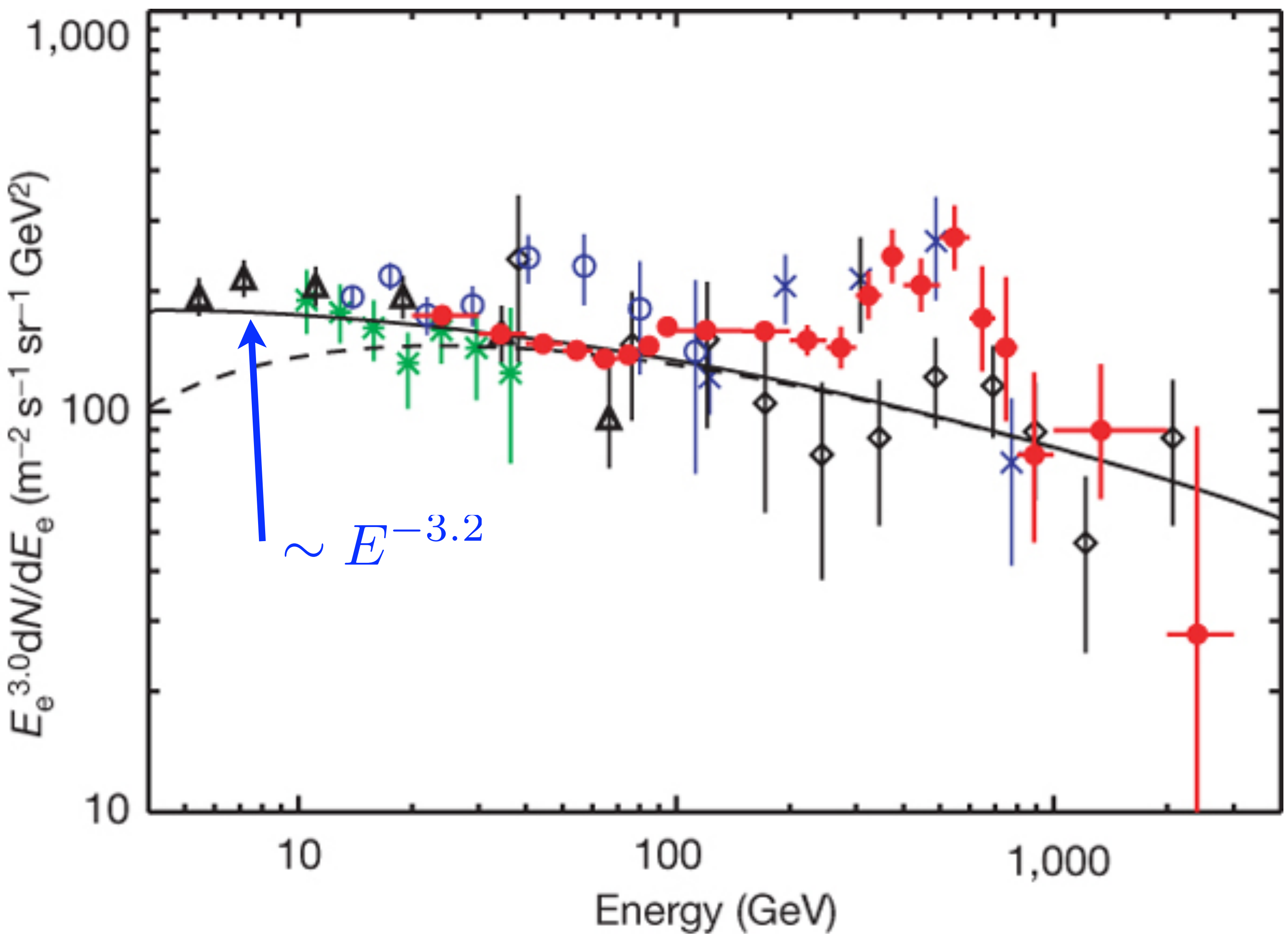


J. Chang *et al.* Nature **456** 362-365 (2008)

ATIC

Electron Spectrum ($e^+ + e^-$)

- "background" can be well described by a power law $E^{-3.2}$



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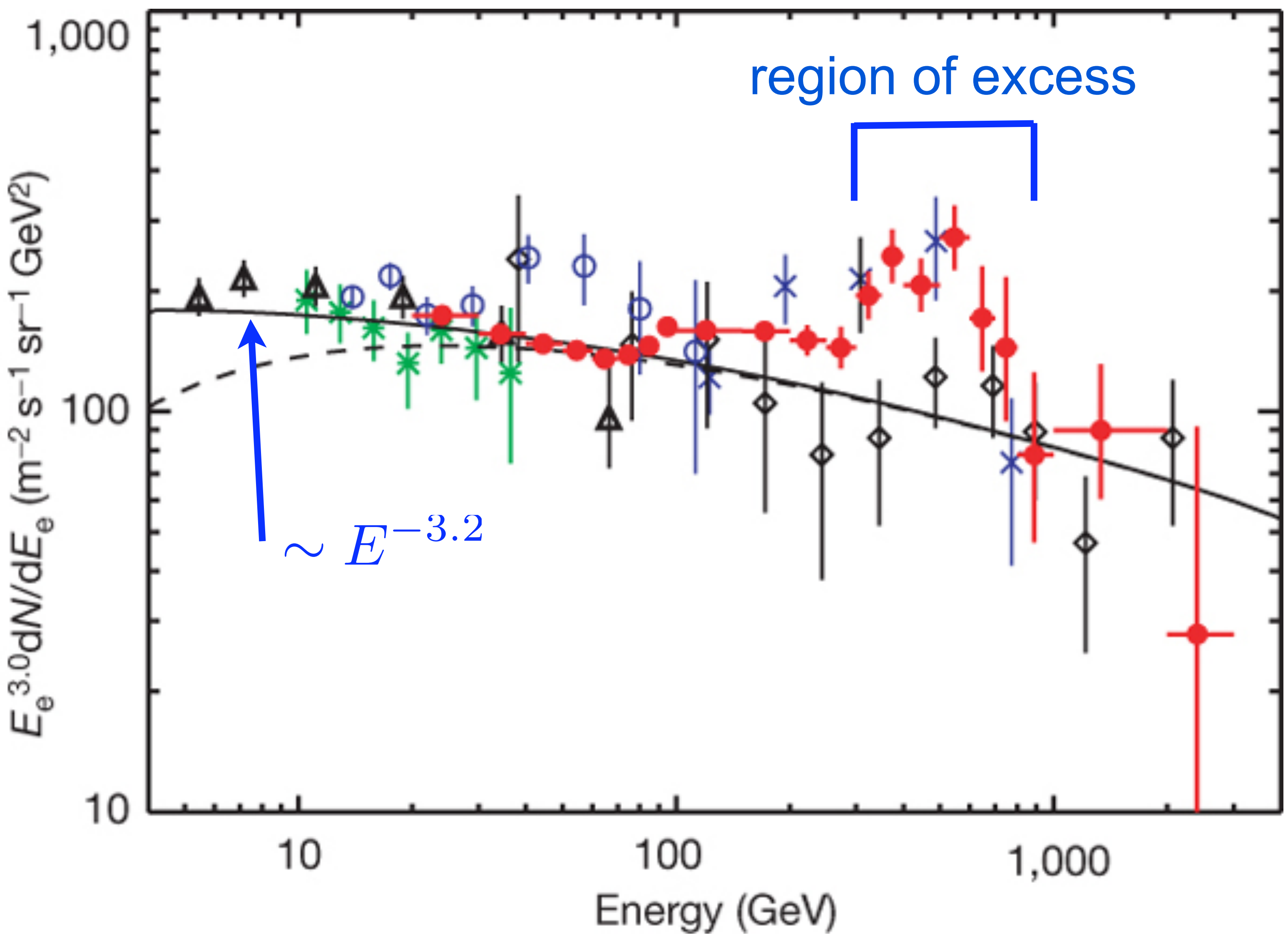
Electron Spectrum ($e^+ + e^-$)

- "background" can be well described by a power law $E^{-3.2}$
- Excess from ~300-800 GeV corresponding to 70 excess electrons out of 210 total



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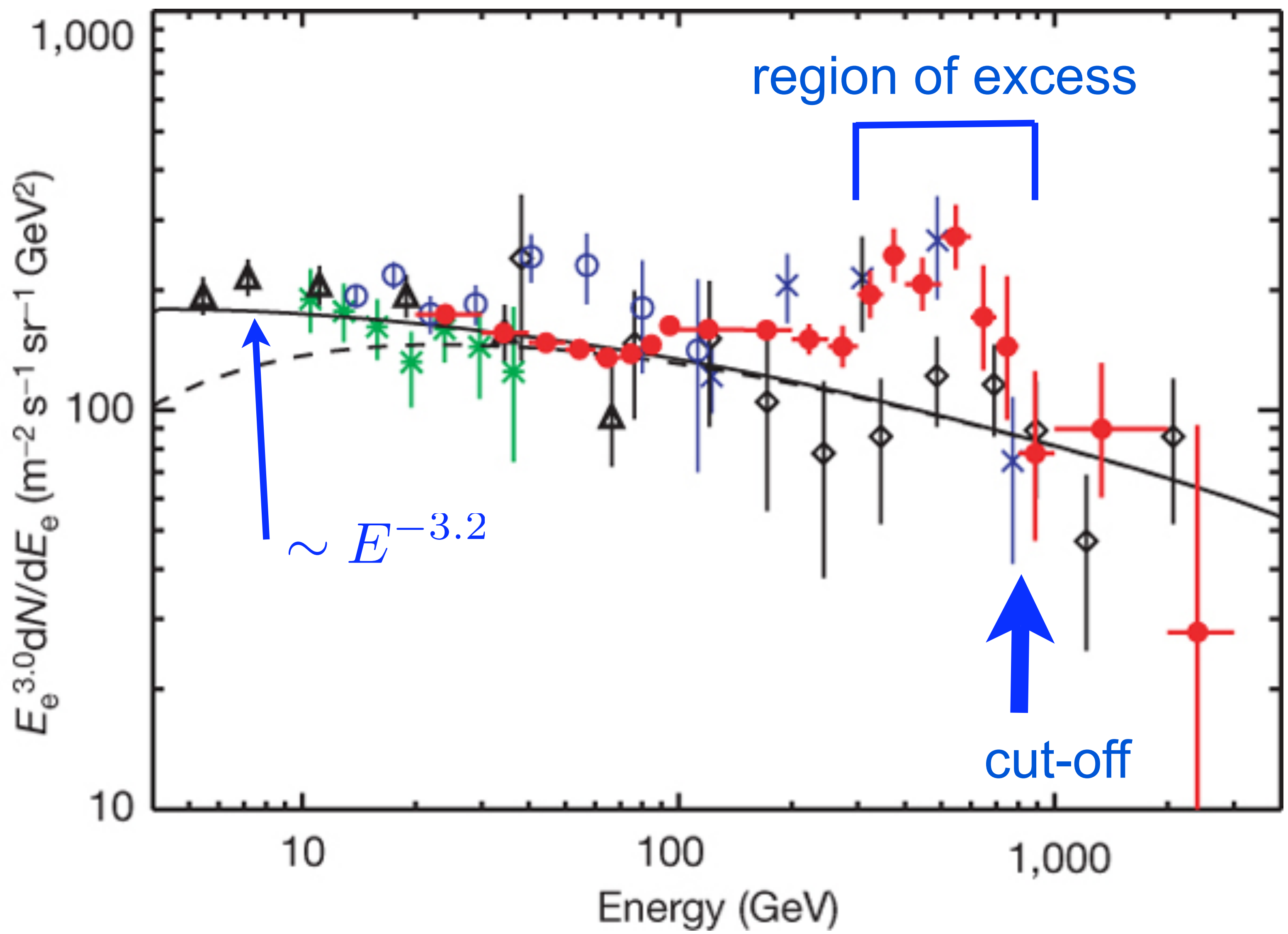
ATIC

Electron Spectrum ($e^+ + e^-$)

- "background" can be well described by a power law $E^{-3.2}$
- Excess from ~300-800 GeV corresponding to 70 excess electrons out of 210 total
- Sharp cut-off in excess at ~800 GeV



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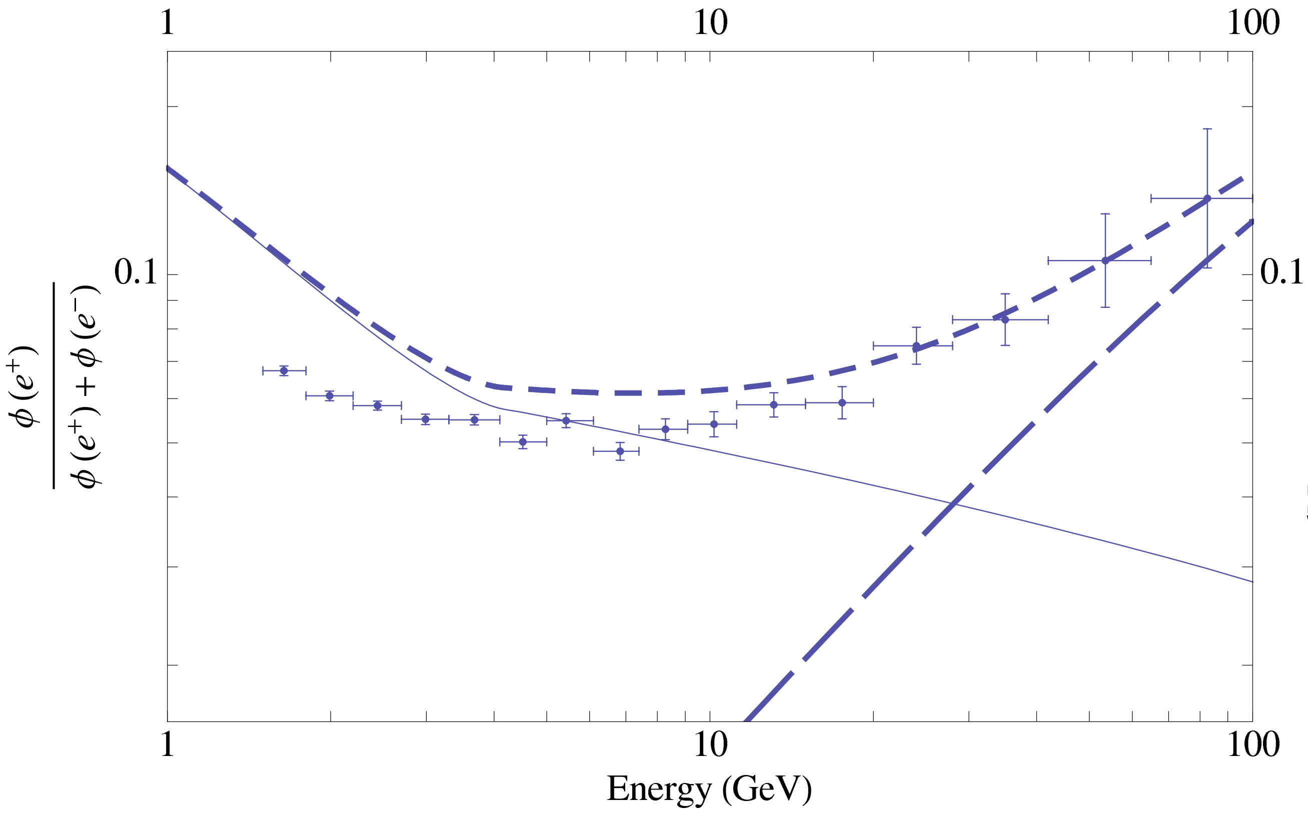
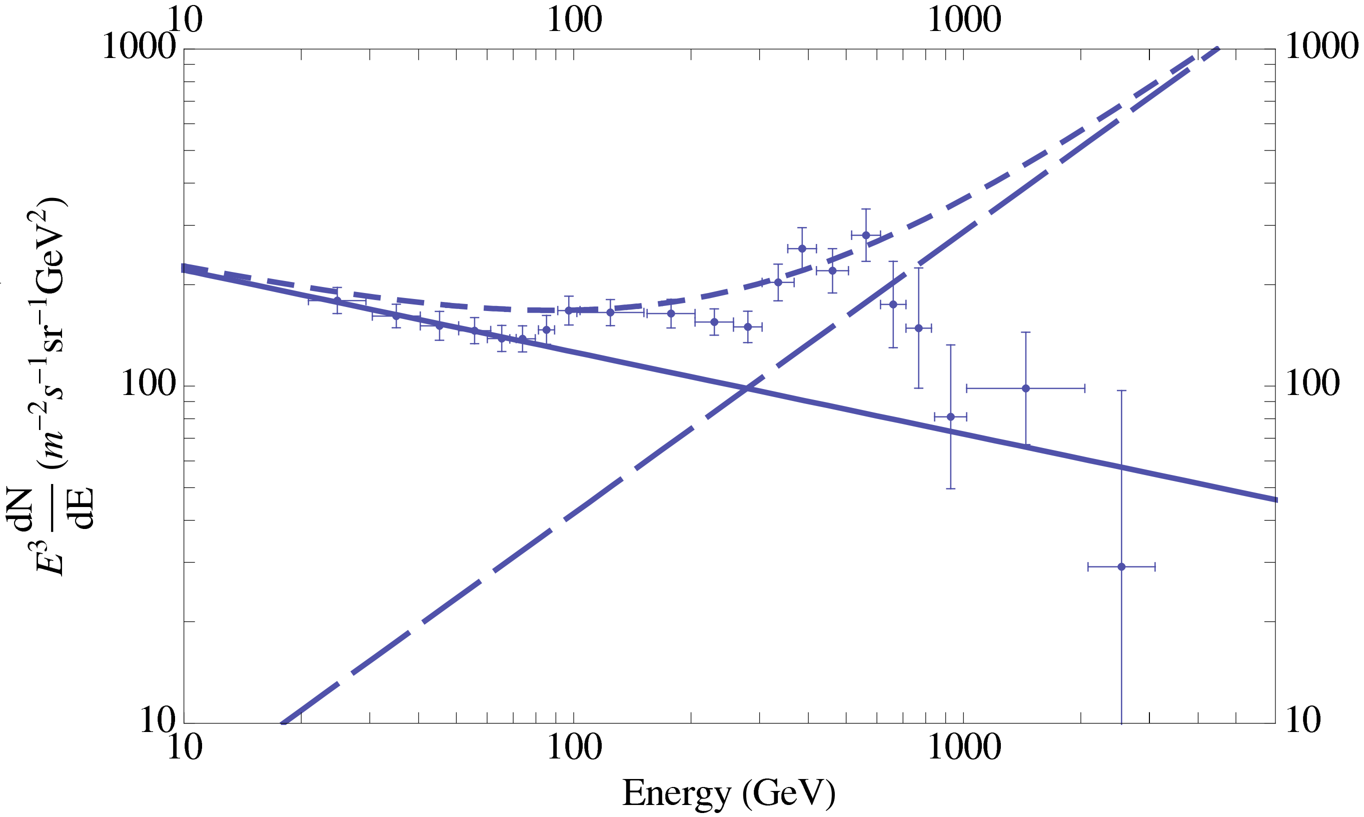
PAMELA



ATIC



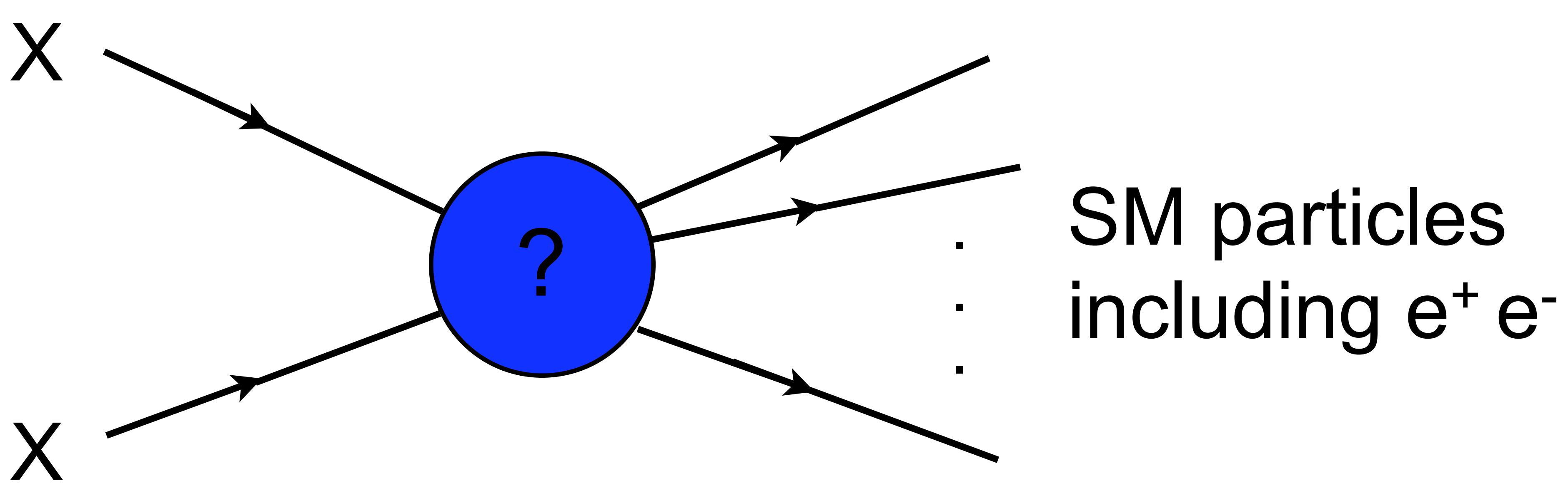
- Extrapolation of the signal at PAMELA naturally leads to an excess in the ATIC energy range similar to the one observed
- This suggests that these two signals arise from the same source

Possible Explanations For Excess High Energy Electrons and Positrons

- Nearby astrophysical object(s), e.g. pulsars

  Büsching *et al.* arXiv:0804.0220
  Hooper *et al.* arXiv:0810.1527
  Profumo arXiv:0812.4457

- Dark Matter Annihilations



GALPROP

Computes the steady-state numerical solution to the propagation equation

$$\frac{\partial n}{\partial t} = q(\vec{r}, E) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} n) + \frac{\partial}{\partial E} \left[b(\vec{r}, E) \; n \right] - \frac{1}{\tau_f} n - \frac{1}{\tau_r} n$$

$n = n(\vec{r}, E, t)$ particle number density per unit energy

incorporates:

- spatial diffusion
- energy losses due to ionization, Coulomb interactions
  bremsstrahlung, inverse Compton and synchrotron
- fragmentation
- decay
- diffusive reacceleration
- convection on Galactic winds

GALPROP

DM Halo

Einasto Profile: $\rho(r) = \rho_0 \; exp[-\frac{2}{\alpha}(\frac{r^\alpha - R_\odot^\alpha}{r^\alpha_{-2}})], \; r^\alpha_{-2} = 25.0 \, \mathrm{kpc}$

$0.13 \leq \alpha \leq 0.22$

NFW Profile: $\rho(r) = \rho_0 \, \frac{r_c}{r} \frac{1}{(1 + \frac{r}{r_c})^2}, \; r_c = 20.0 \text{ kpc}$

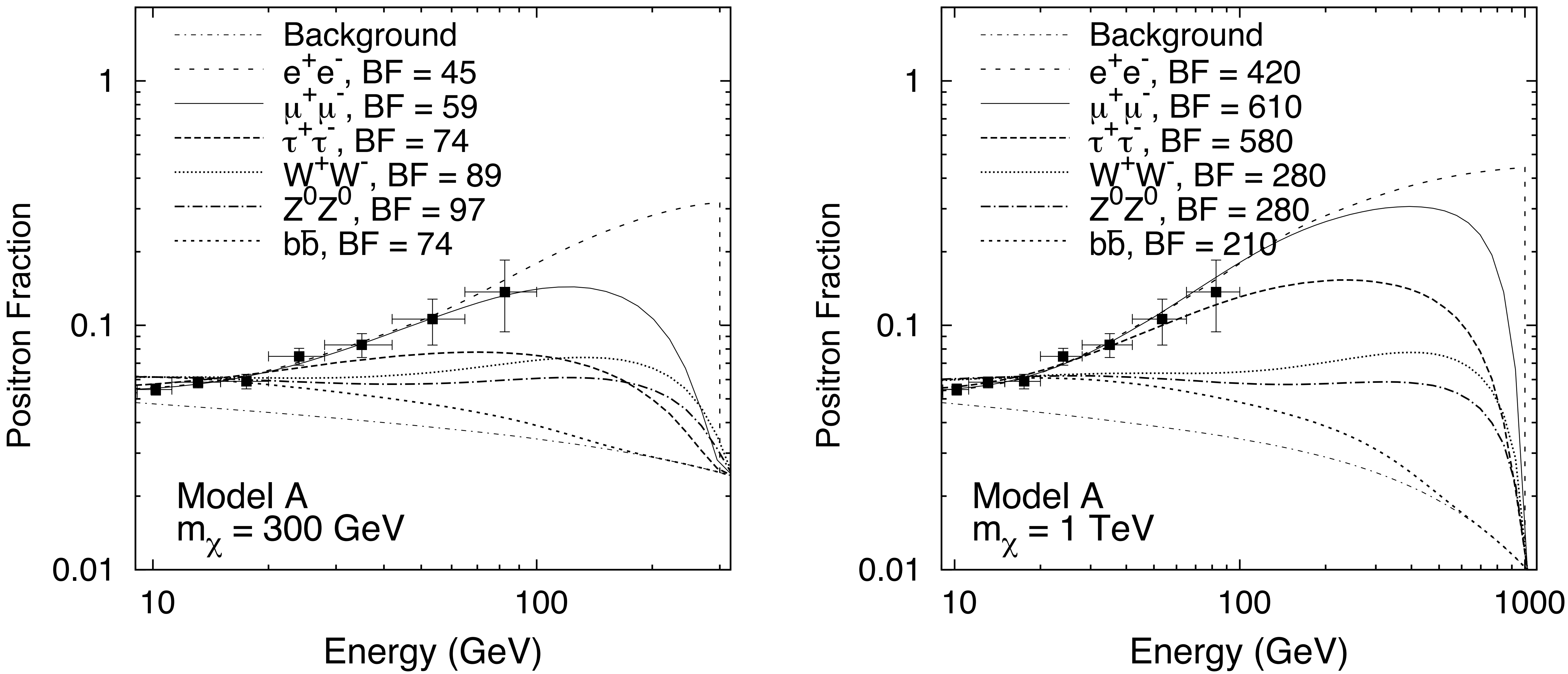
we take $\rho(R_\odot) = 0.30 - 0.35 \text{ GeV cm}^{-3}$, $\alpha = 0.17$

Galactic Magnetic Field

$$B_{tot} = B_0 \, e^{-(R - R_\odot)/R_B - |z|/z_B}$$

with $B_0 = 5 \; \mu G, \, \mathrm{R}_B = 10 \text{ kpc}, \; z_B = 2 \text{ kpc}$

PAMELA Positron Fraction



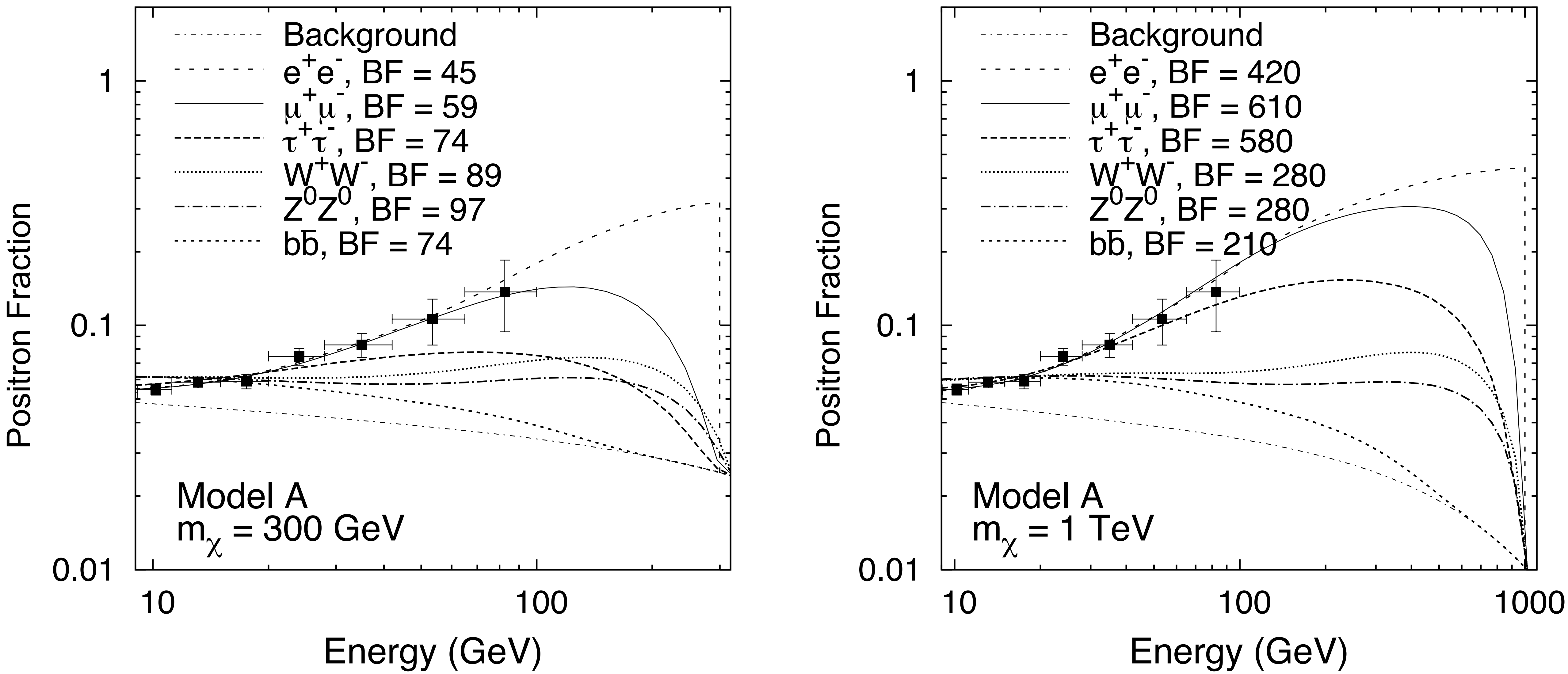
Cholis, LG, Hooper, Simet, Weiner arXiv:0809.1683

$$\chi\,\chi \longrightarrow e^+e^-$$

$$\chi\,\chi \longrightarrow \mu^+\mu^- \longrightarrow e^+e^-$$

$$\vdots$$

PAMELA Positron Fraction

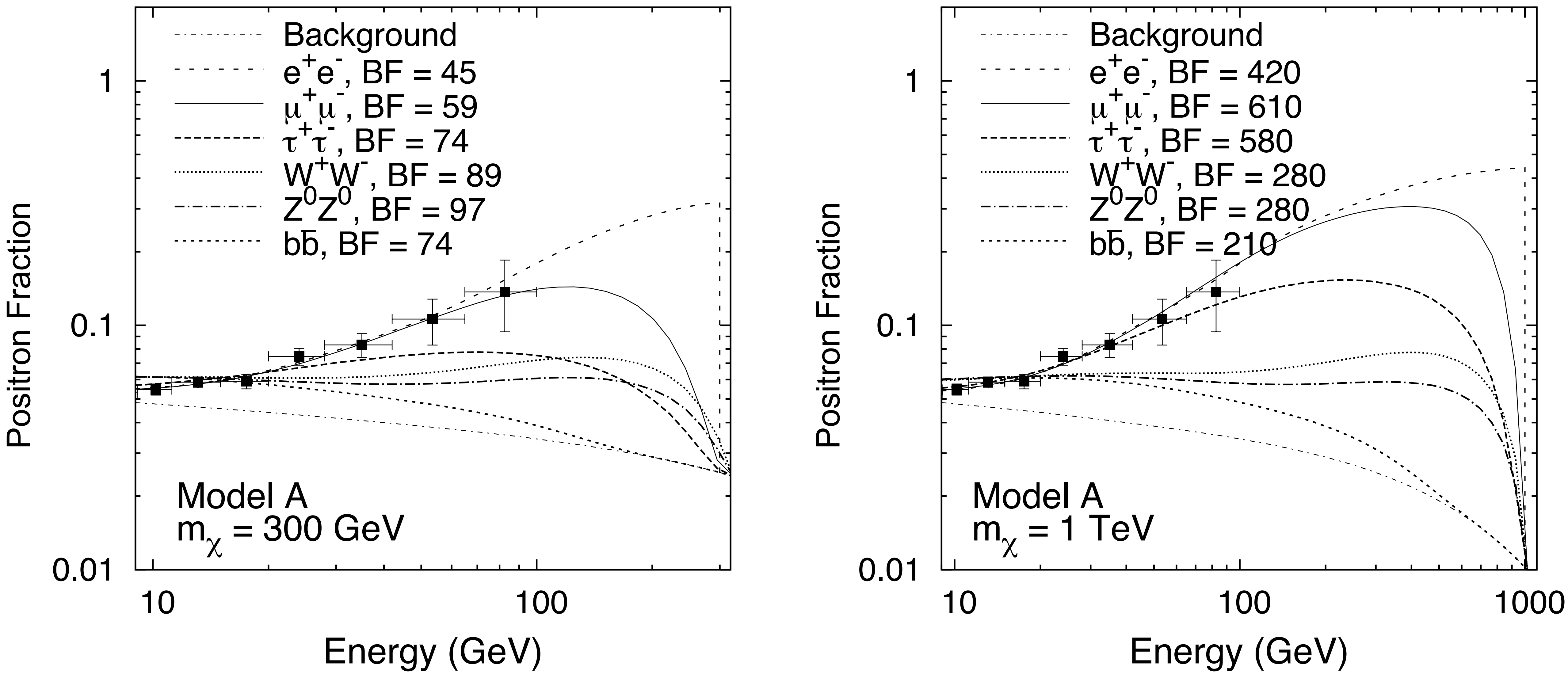


Cholis, LG, Hooper, Simet, Weiner arXiv:0809.1683

We define: $$\Gamma_{ann} = BF * \left(\frac{\rho_0}{m_\chi}\right)^2 \langle \sigma_{ann} |v| \rangle$$

$$\rho(R_\odot) = 0.35 \text{ GeV cm}^{-3} \;, \quad \langle \sigma_{ann} |v| \rangle = 3.0 \times 10^{-26} \text{ cm}^3\text{s}^{-1}$$

PAMELA Positron Fraction



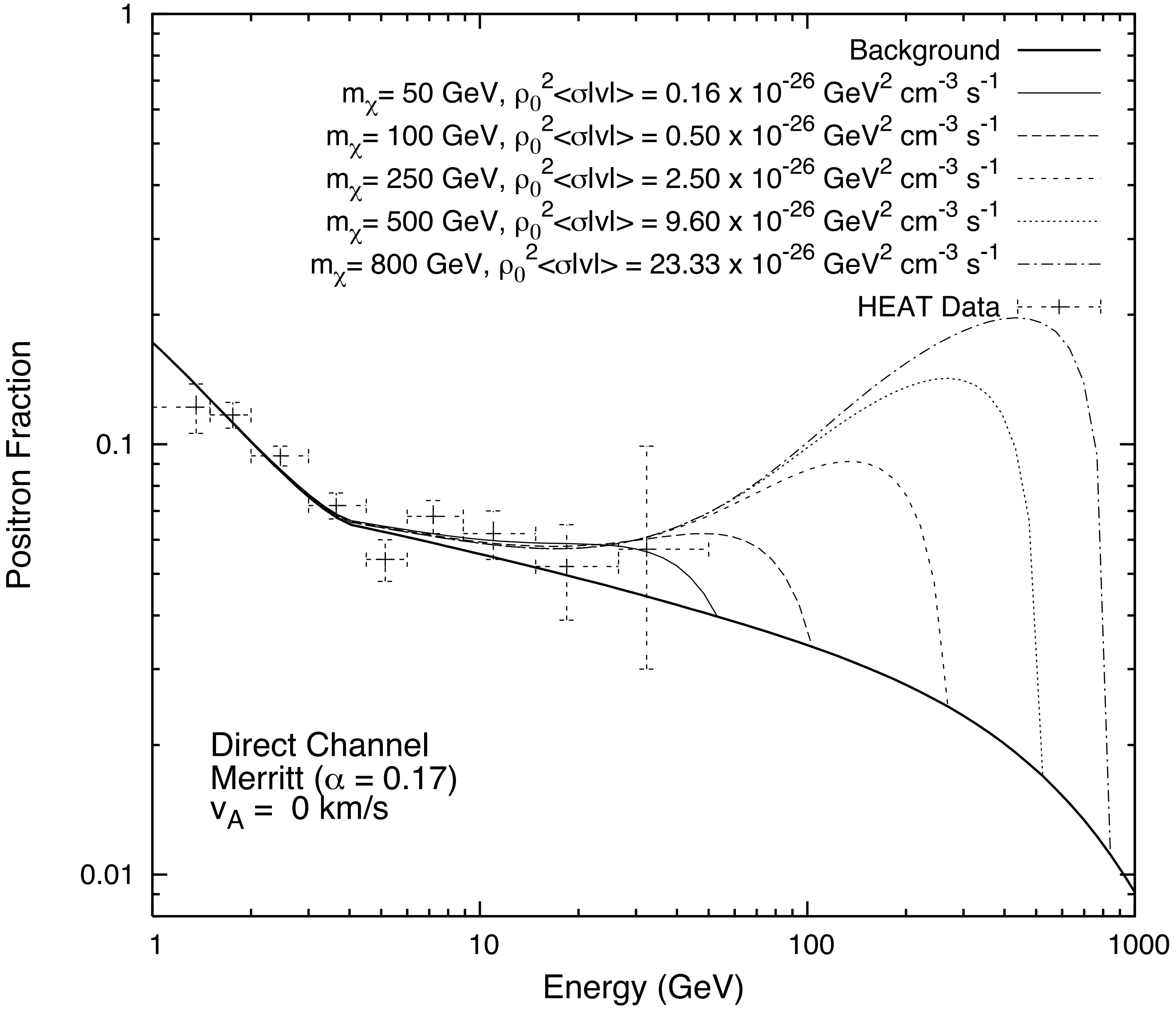
Cholis, LG, Hooper, Simet, Weiner arXiv:0809.1683

For $m_\chi = 300$ GeV only the annihilation channels $\chi\chi \longrightarrow e^-e^+$ and $\chi\chi \longrightarrow \mu^-\mu^+$ give good fits to the PAMELA data

For $m_\chi = 1$ TeV the annihilation channels to all charged leptons give good fits to PAMELA

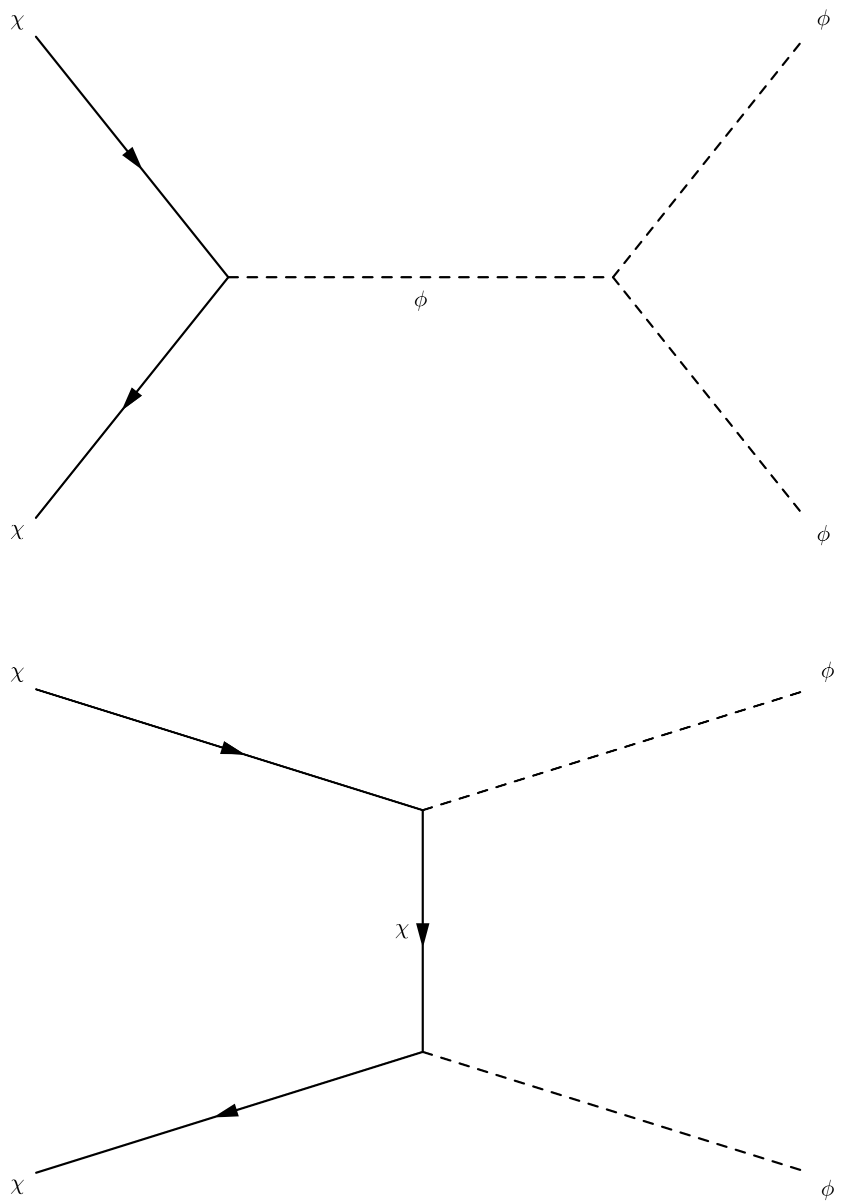
eXciting Dark Matter (XDM)

February '08



Cholis, LG, Weiner arXiv:0802.2922

$$\chi\,\chi \longrightarrow \phi\,\phi \longrightarrow e^- e^+$$



eXciting Dark Matter (XDM)

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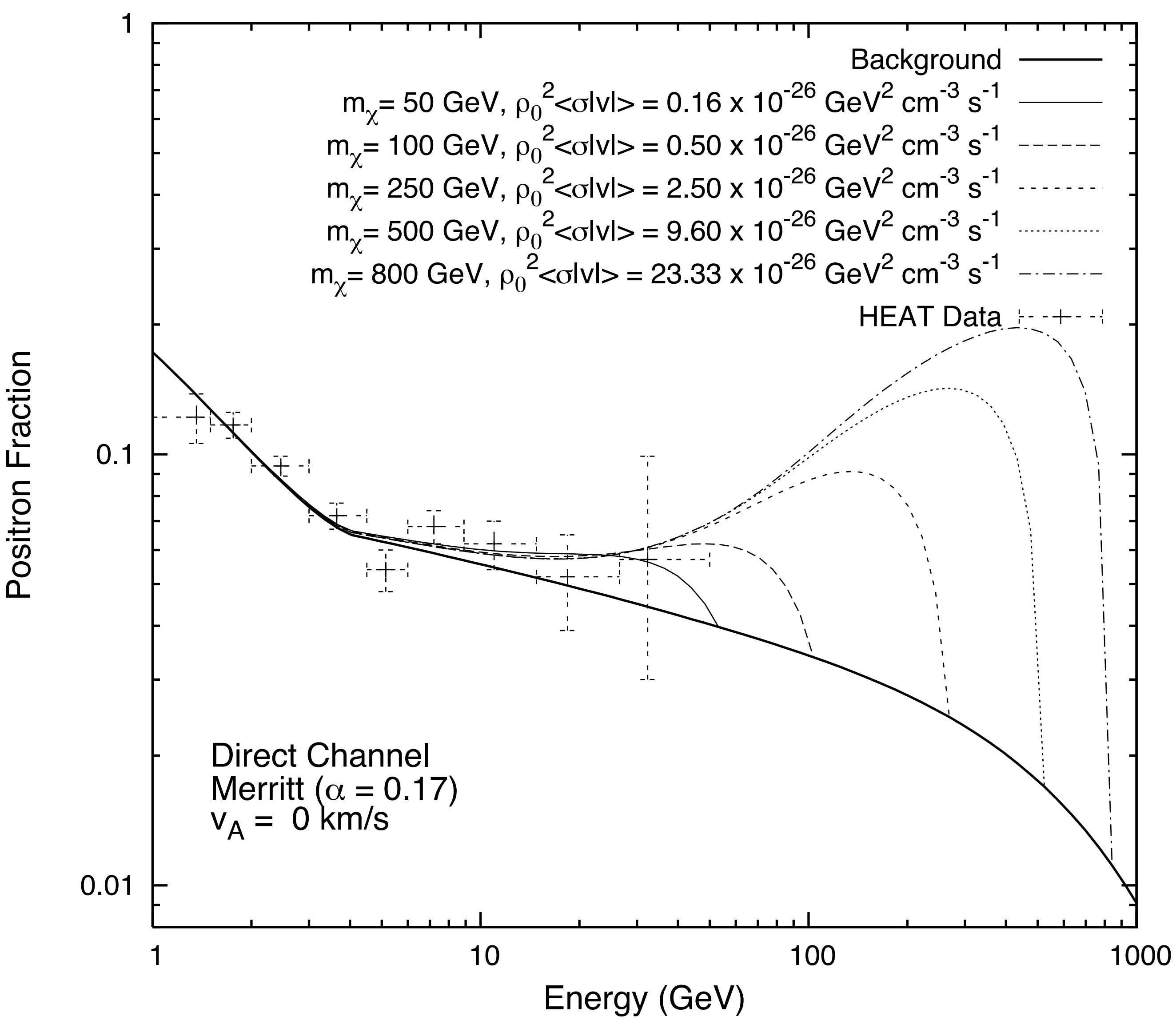
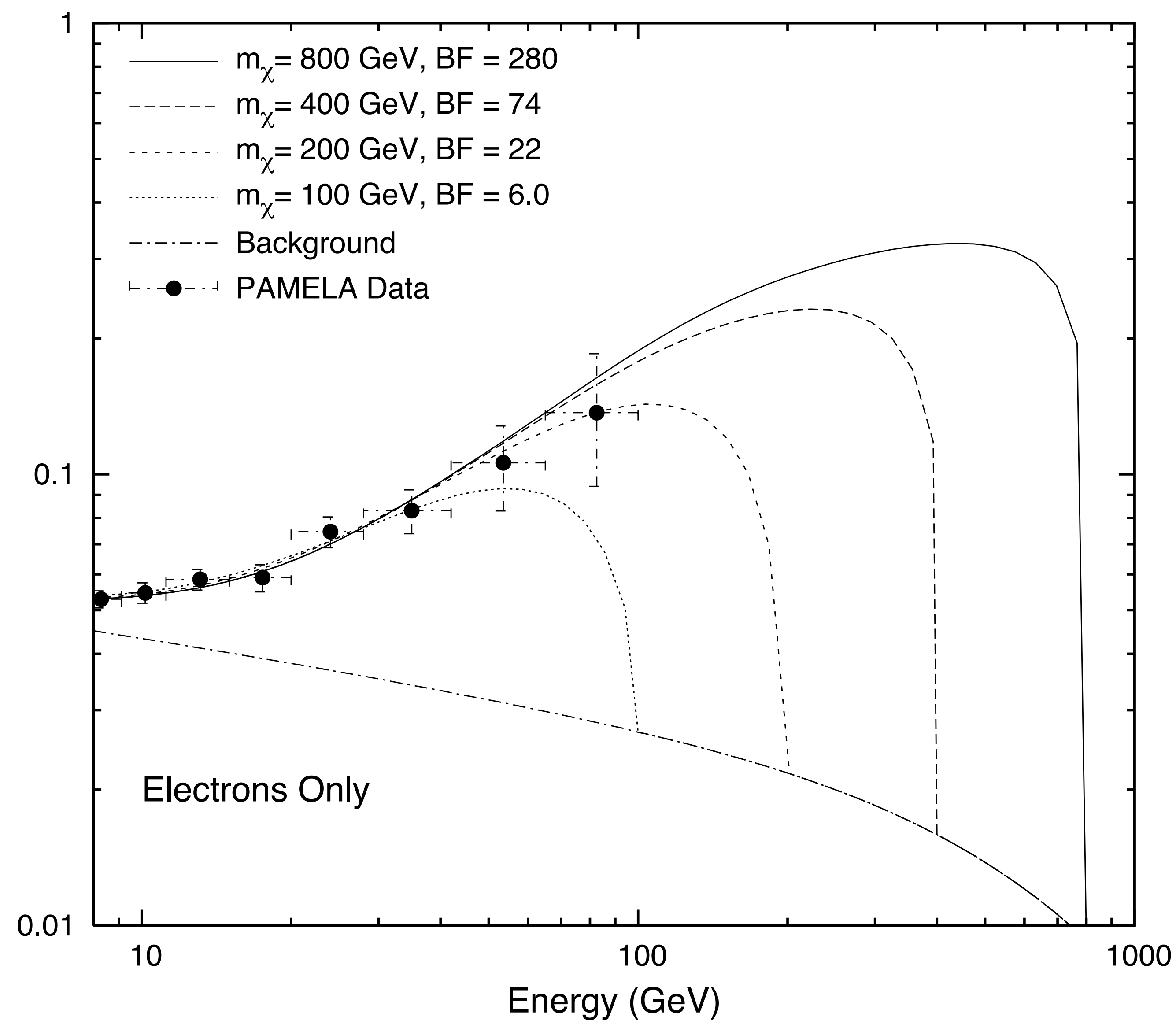


Cholis, LG, Weiner arXiv:0802.2922

October ‘08



Cholis, Finkbeiner, LG, Weiner arXiv:0810.5344

eXciting Dark Matter (XDM)

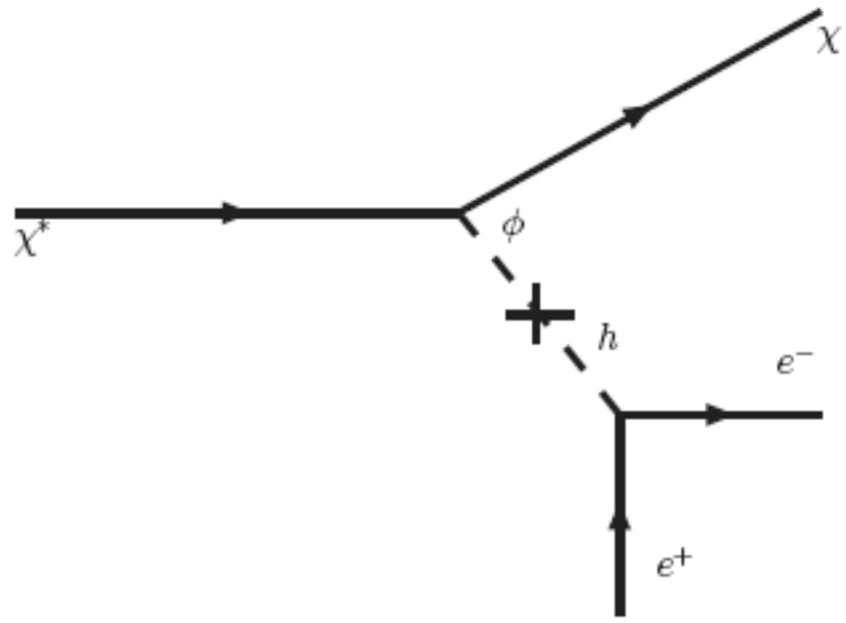
INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory) has measured the 511 keV line coming from direct annihilation of $e^+ e^-$ pairs and decay of para-positronium

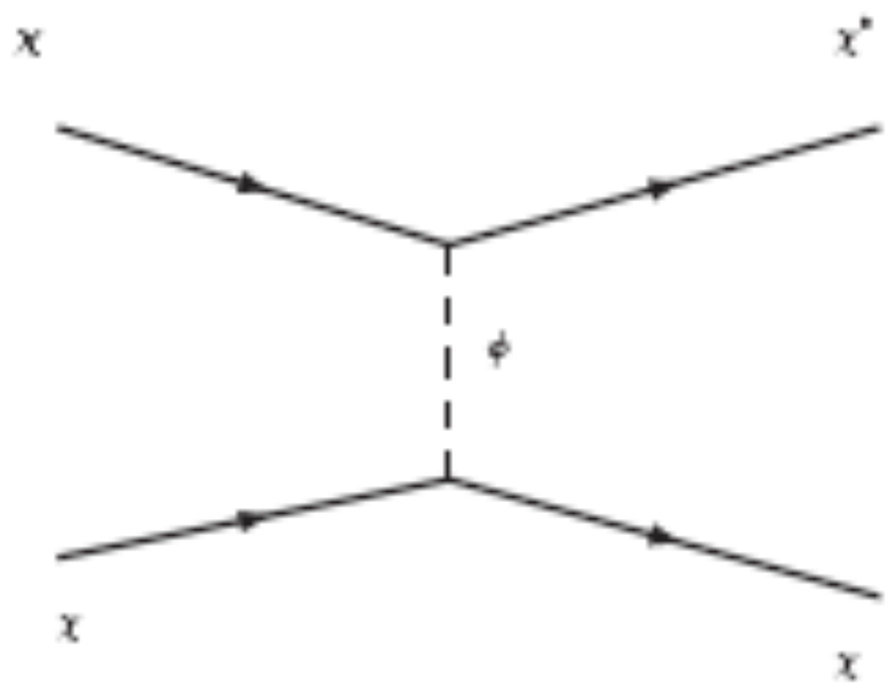
- Signal corresponds to an annihilation rate of 3×10^{42} $e^+ e^-$ pairs/sec
- Signal is strongest in GC indicating that this region has the largest concentration of annihilation
- It is a challenge for conventional astrophysical sources to explain the signal

eXciting Dark Matter (XDM)

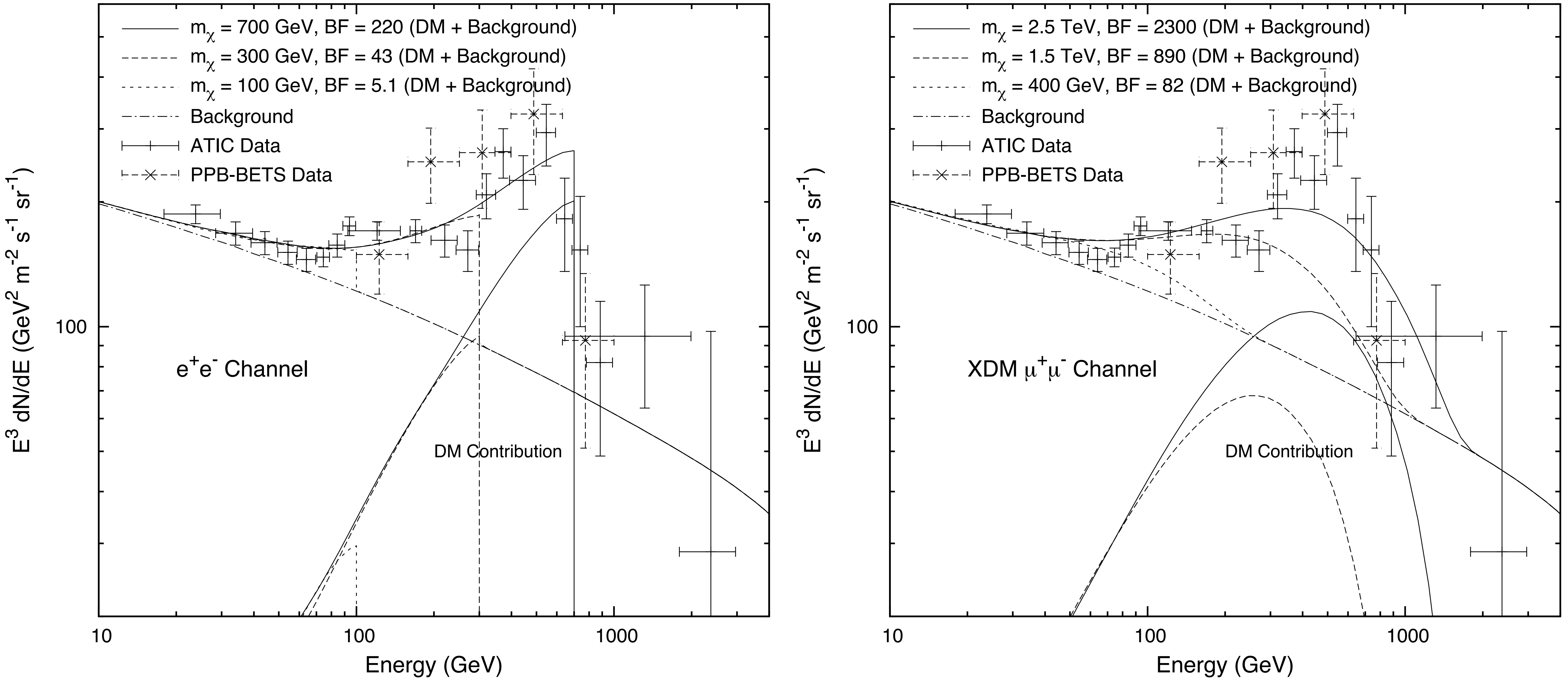
Finkbeiner and Weiner (astro-ph/0702587) proposed that the $e^+ e^-$ pairs are created in the decay of an excited state of dark matter

- Excited state has an energy at least $2m_e$ above the ground state
- Energy needed for the excitation process comes from the kinetic energy of WIMPS (inelastic collisions)
- Coupling to SM occurs through a light mediator which couples to the higgs
- DM has weak-scale mass





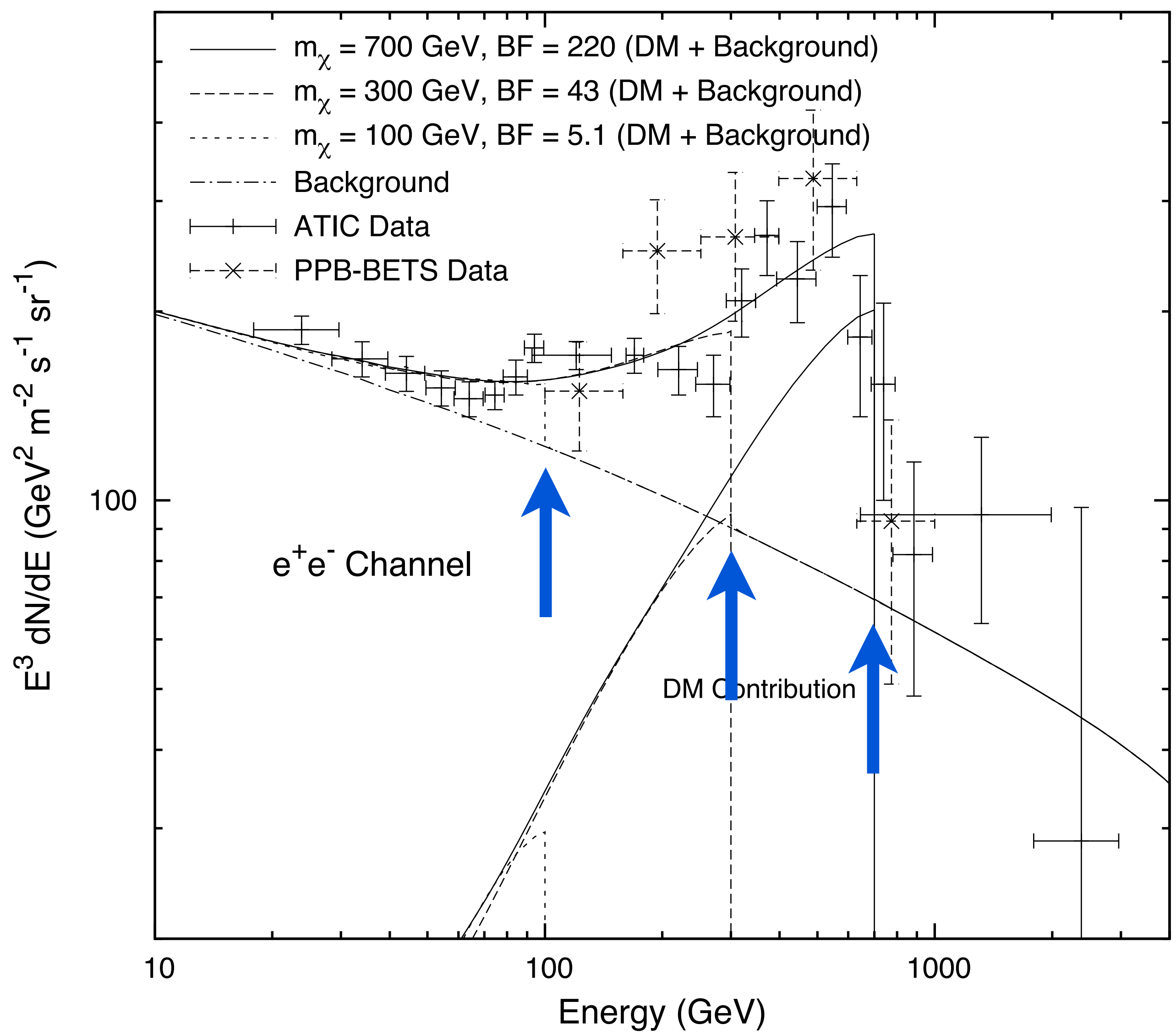
ATIC Electron Flux

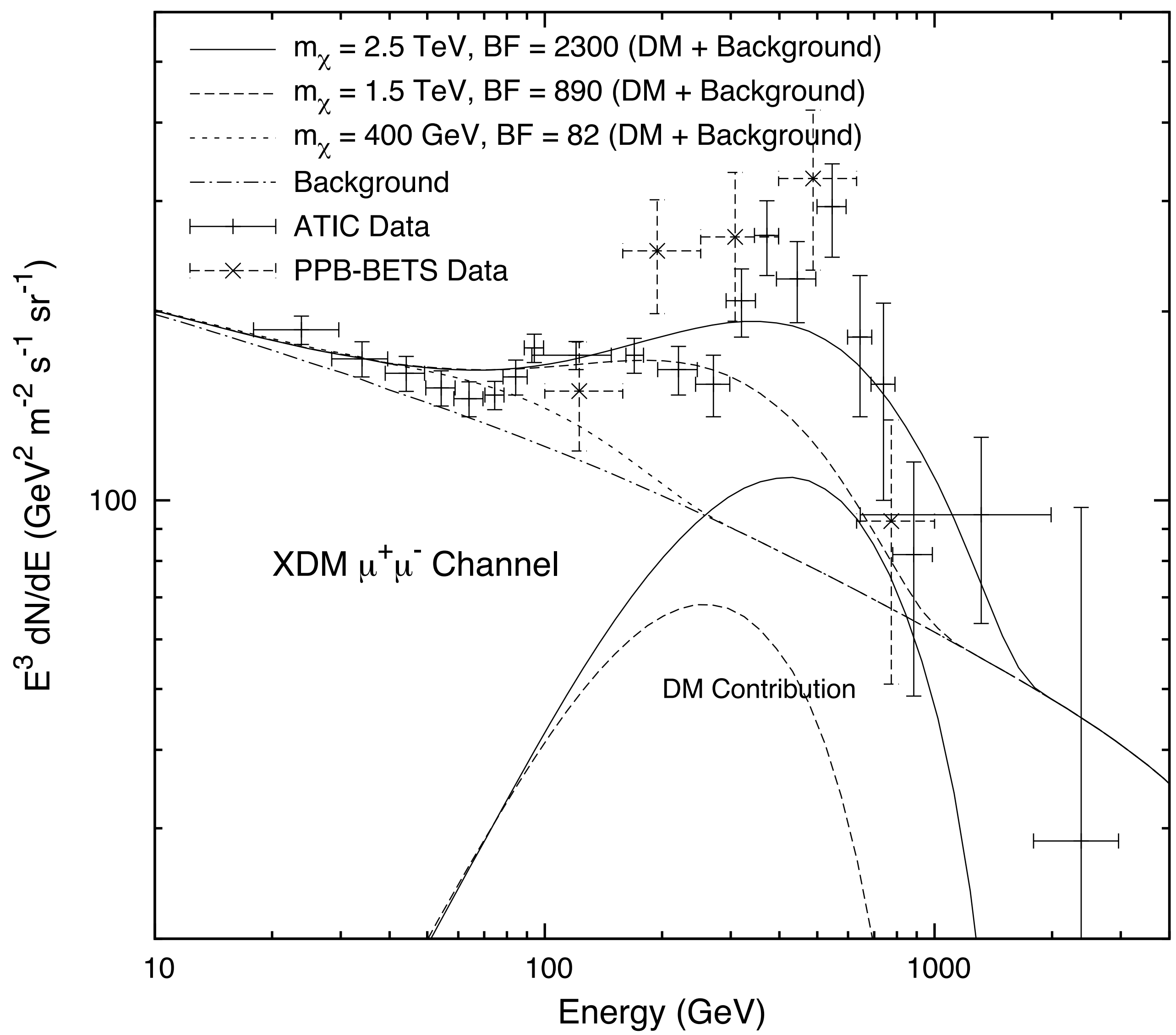


Cholis, Dobler, Finkbeiner, LG, Weiner arXiv:0811.3641

- Annihilation modes with hard positron spectra also fit ATIC well
- ATIC requires much higher DM masses than PAMELA
- Large boost factors are required

ATIC Electron Flux

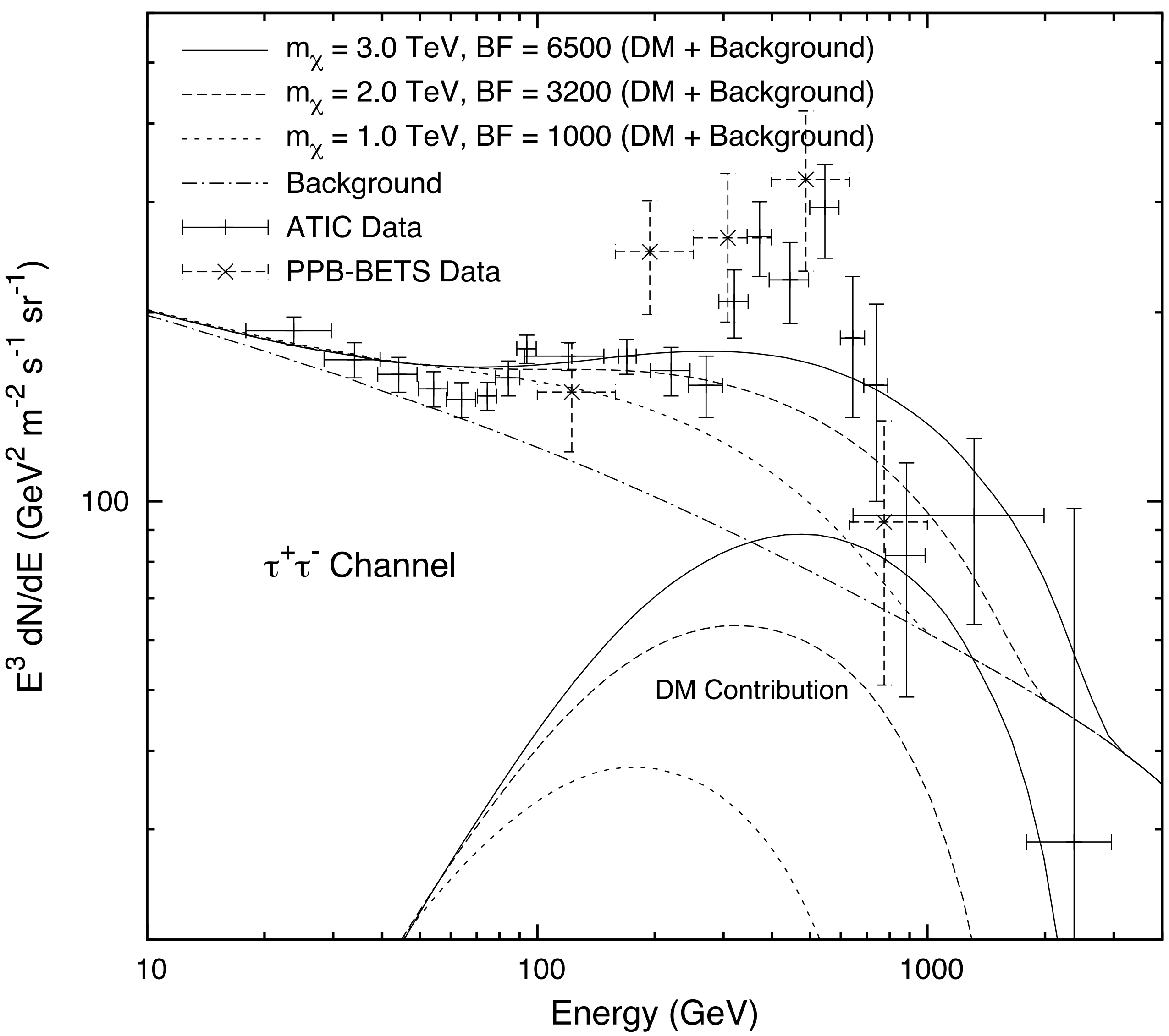


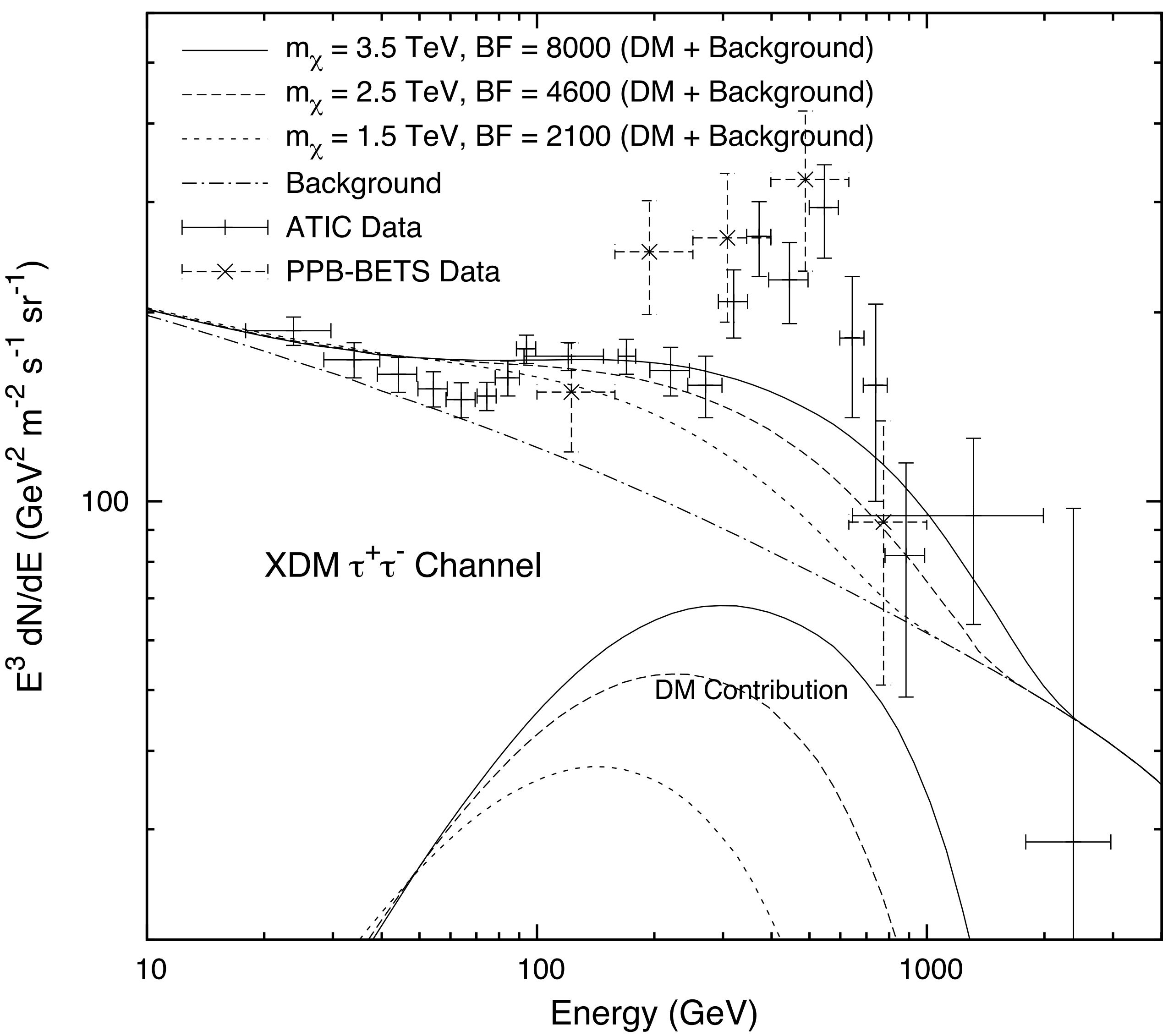


Cholis, Dobler, Finkbeiner, LG, Weiner arXiv:0811.3641

- Annihilation modes with hard positron spectra also fit ATIC well
- ATIC requires much higher DM masses than PAMELA
- Large boost factors are required
- Sharp fall-off at DM mass for e^+ e^- channels (including XDM)

ATIC Electron Flux

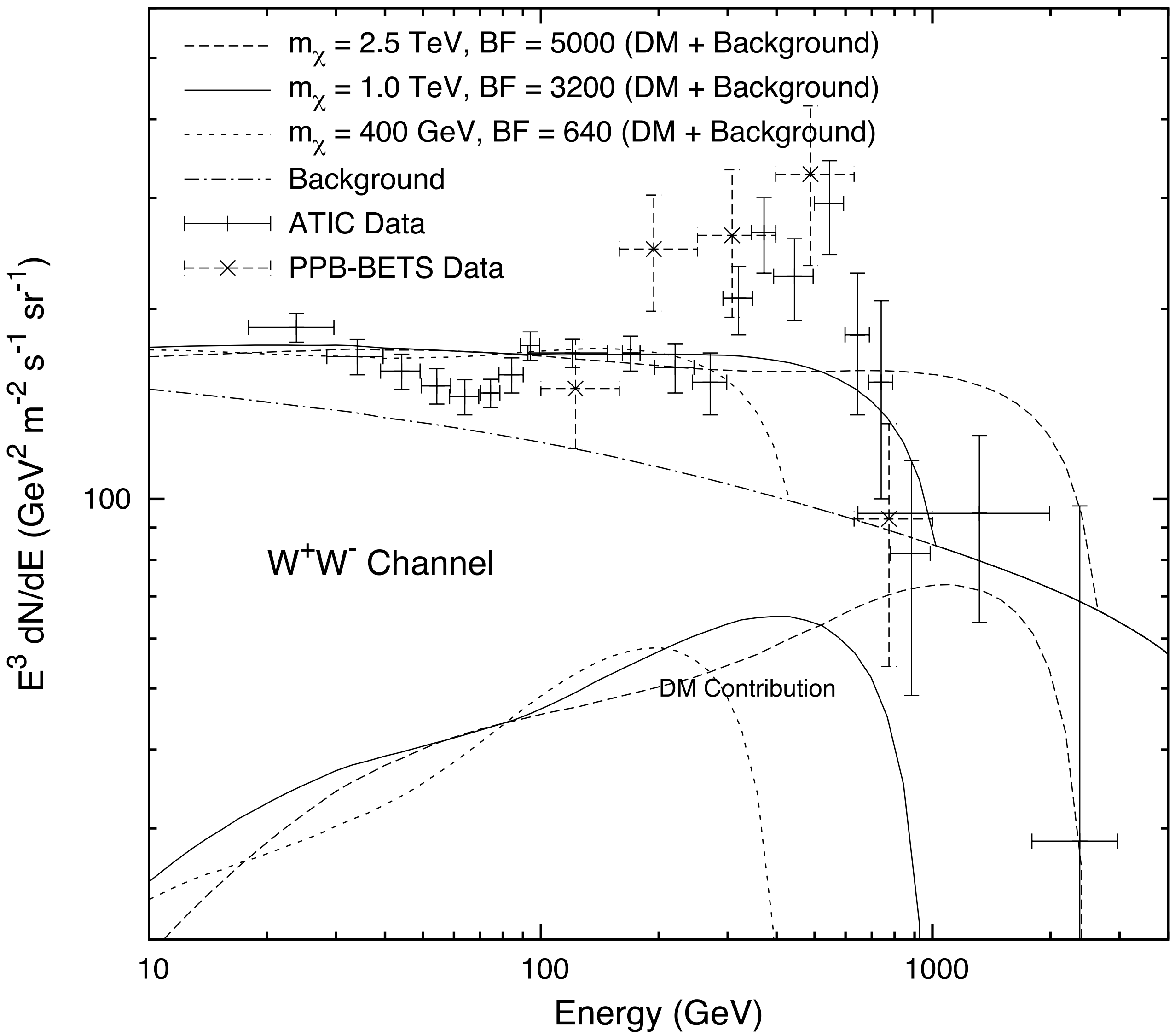




Cholis, Dobler, Finkbeiner, LG, Weiner arXiv:0811.3641

- Fits for annihilation into taus are not as good
- Spectrum is softer, so low energy e^+ are mildly over produced while high energy e^+ are underproduced

ATIC Electron Flux



Cholis, Dobler, Finkbeiner, LG, Weiner arXiv:0811.3641

$$W^+ W^- \longrightarrow e^+ e^- \quad \sim 10.8\%$$

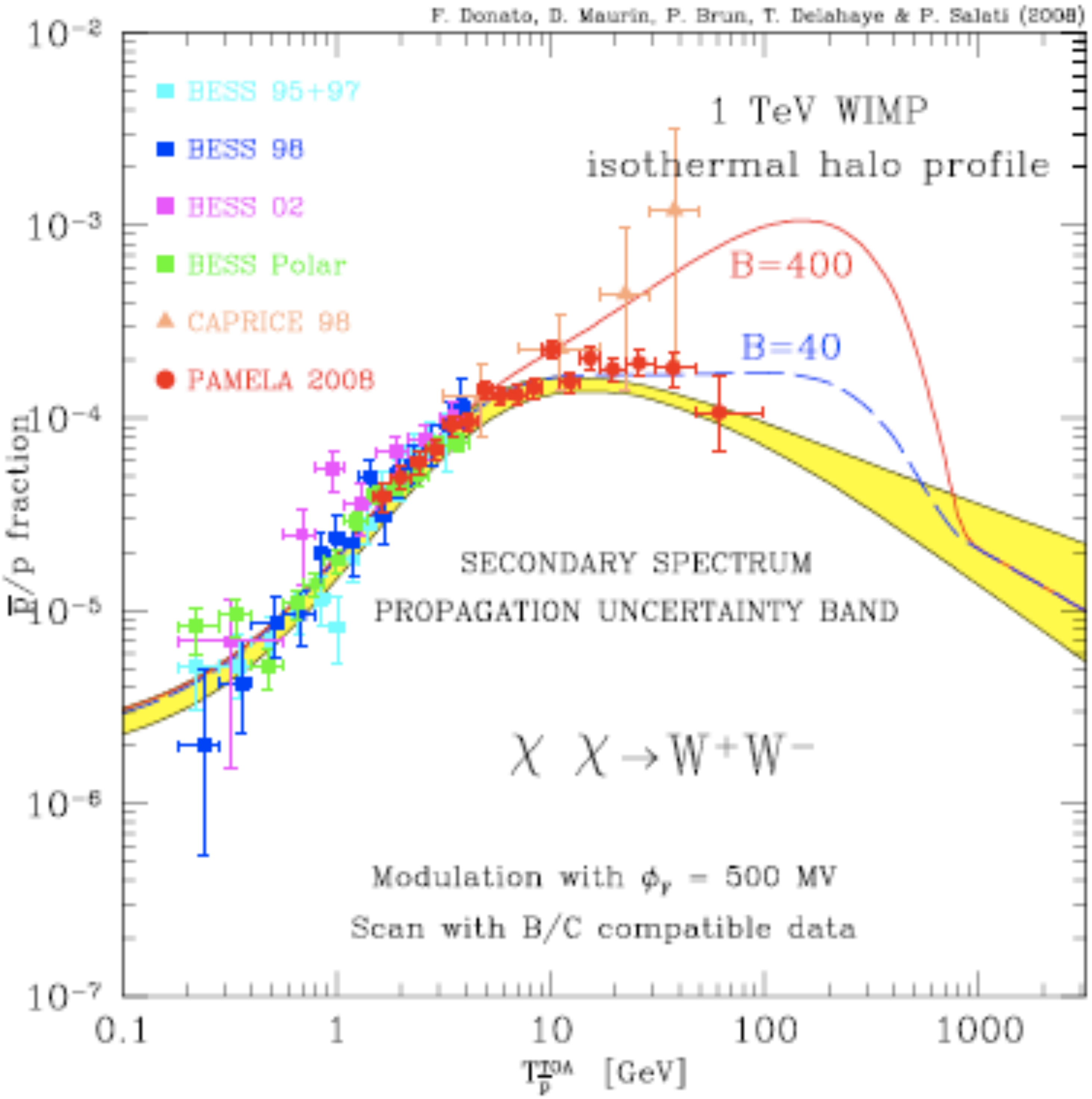
$$W^+ W^- \longrightarrow \mu^+ \mu^- \quad \sim 10.6\%$$

- Fits for annihilation into W's are poor
- Most positrons from W's come from hadronic decay chain and so are soft

PAMELA Antiproton Fraction $\frac{\bar{p}}{p}$

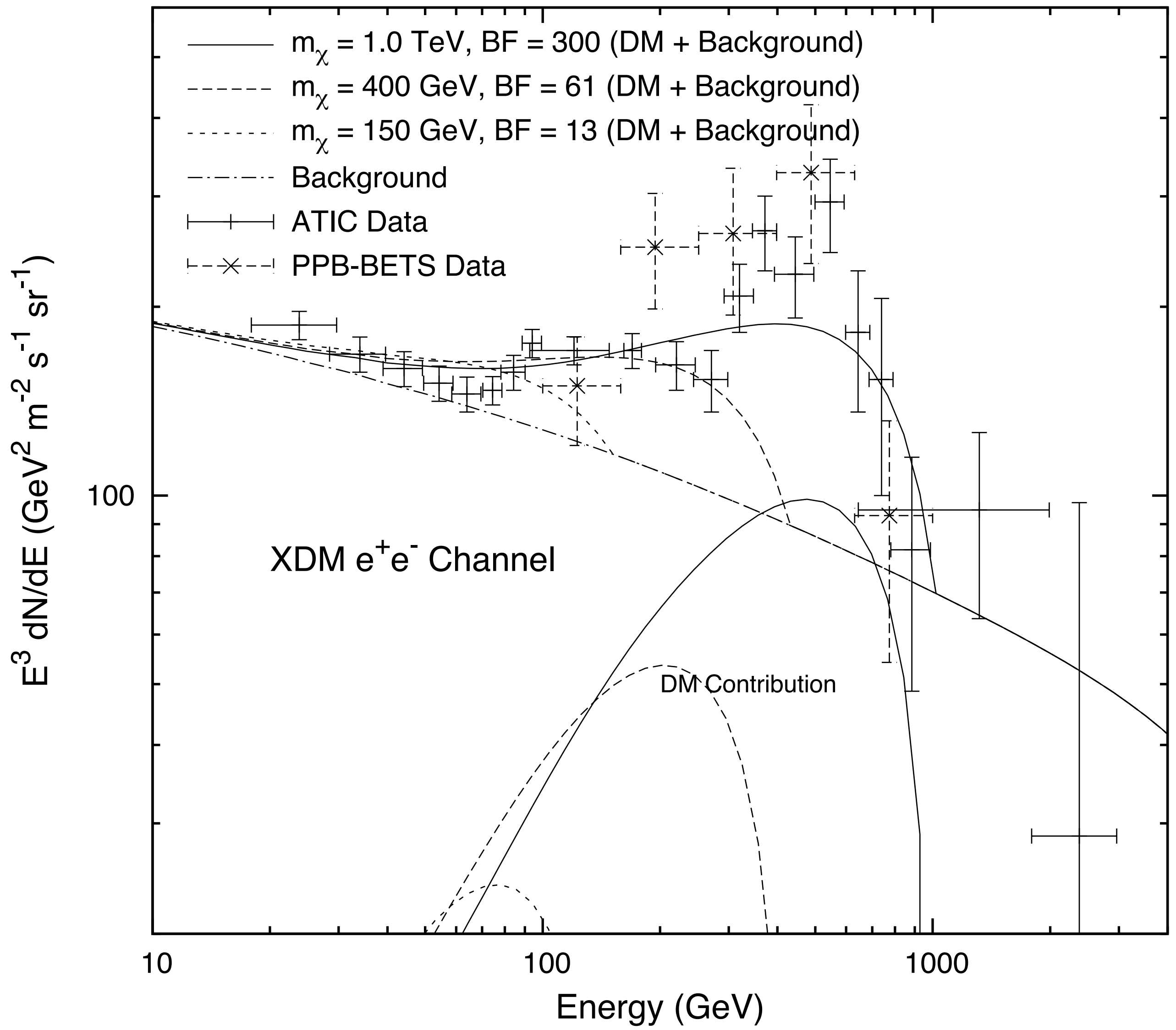
- Donato *et al.* found that for a 1TeV DM particle annihilating into W's, the BF cannot exceed 40

- Our fits to ATIC (BF~3200) and PAMELA (BF~1000) require BF's that are seriously at odds with this constraint

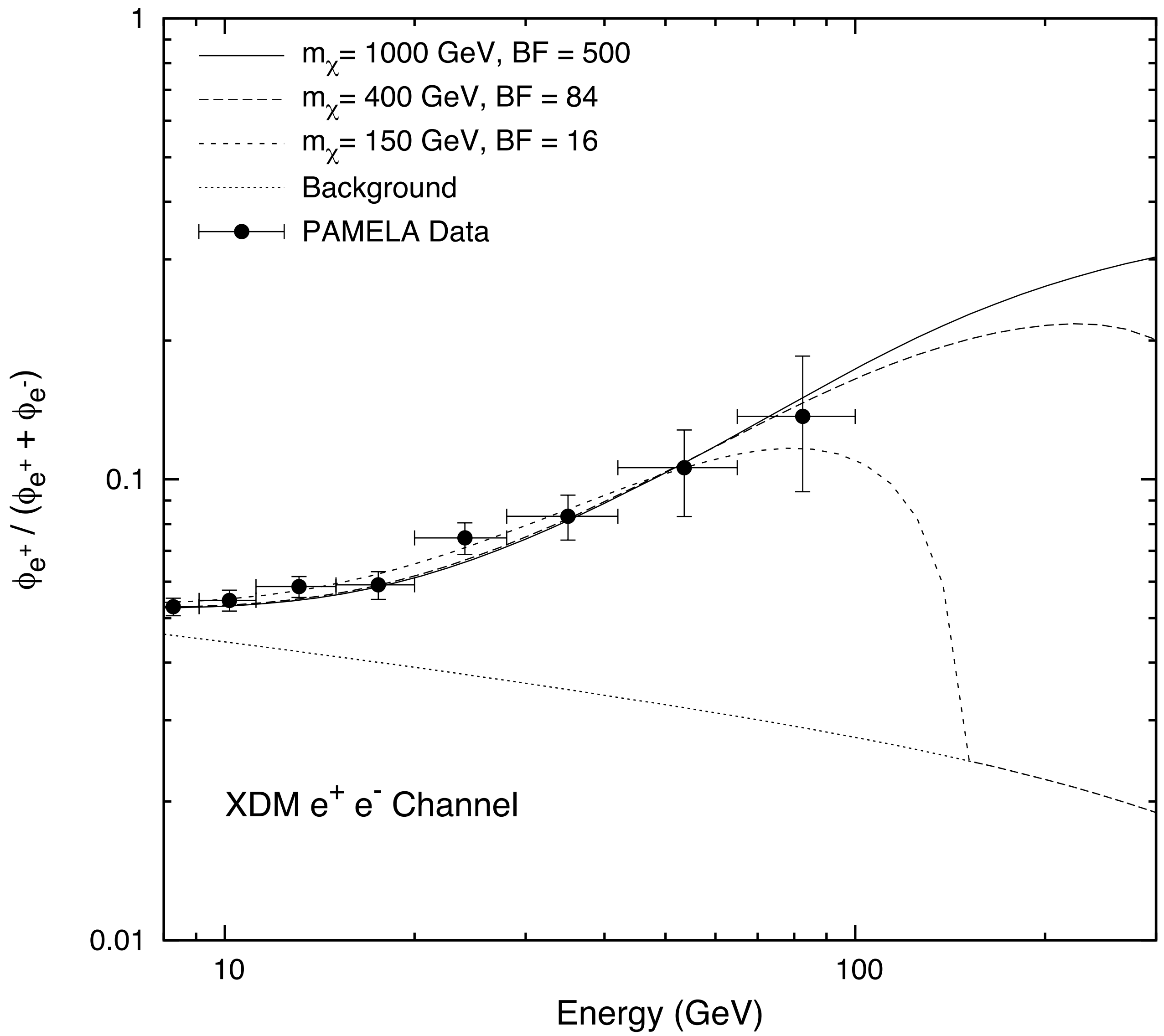


Donato *et al* arXiv:0810.5292

ATIC



PAMELA



Cholis, Dobler, Finkbeiner, LG, Weiner arXiv:0811.3641

In summary,
DM annihilations into charged leptons, directly or through a light mediator (XDM scenario), can explain both the PAMELA and ATIC anomalies with similar, although large, boost factors

How can we explain the large annihilation rates?

We expect some enhancement of the signal from substructure in the DM halo. This is just a restatement of the relation $\langle \rho^2 \rangle \geq \langle \rho \rangle^2$. But this is expected to contribute by a factor of 10 or less.

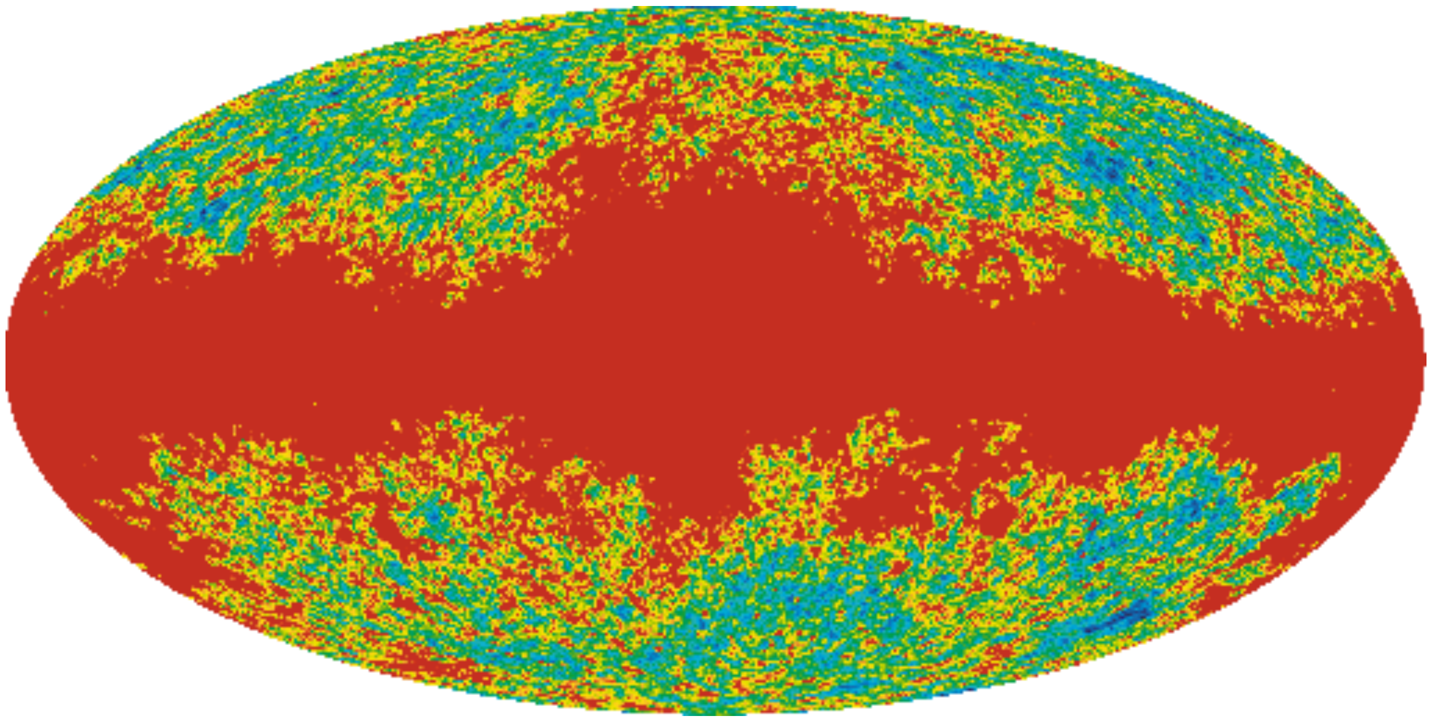
Theories involving a light force carrier can have an enhanced annihilation cross-section at low velocities due to the "Sommerfeld enhancement" where $\sigma v \sim 1/v$. The cross-section can be increased by up to two orders of magnitude in subhalos where the velocity dispersion is much lower than in the halo.

The presence of a nearby clump of Dark Matter can give enhanced particle fluxes that would be interpreted as large annihilation rates, while the cross-section and DM density take standard values.

WMAP

Wilkinson Microwave Anisotropy Probe

- Measures microwave emission at 22.5, 32.7, 40.6, 60.7, 93.1 GHz
- Galactic foreground signals include thermal dust, free-free (thermal bremsstrahlung), “ordinary” synchrotron from relativistic e^- accelerated by SN, and spinning dust

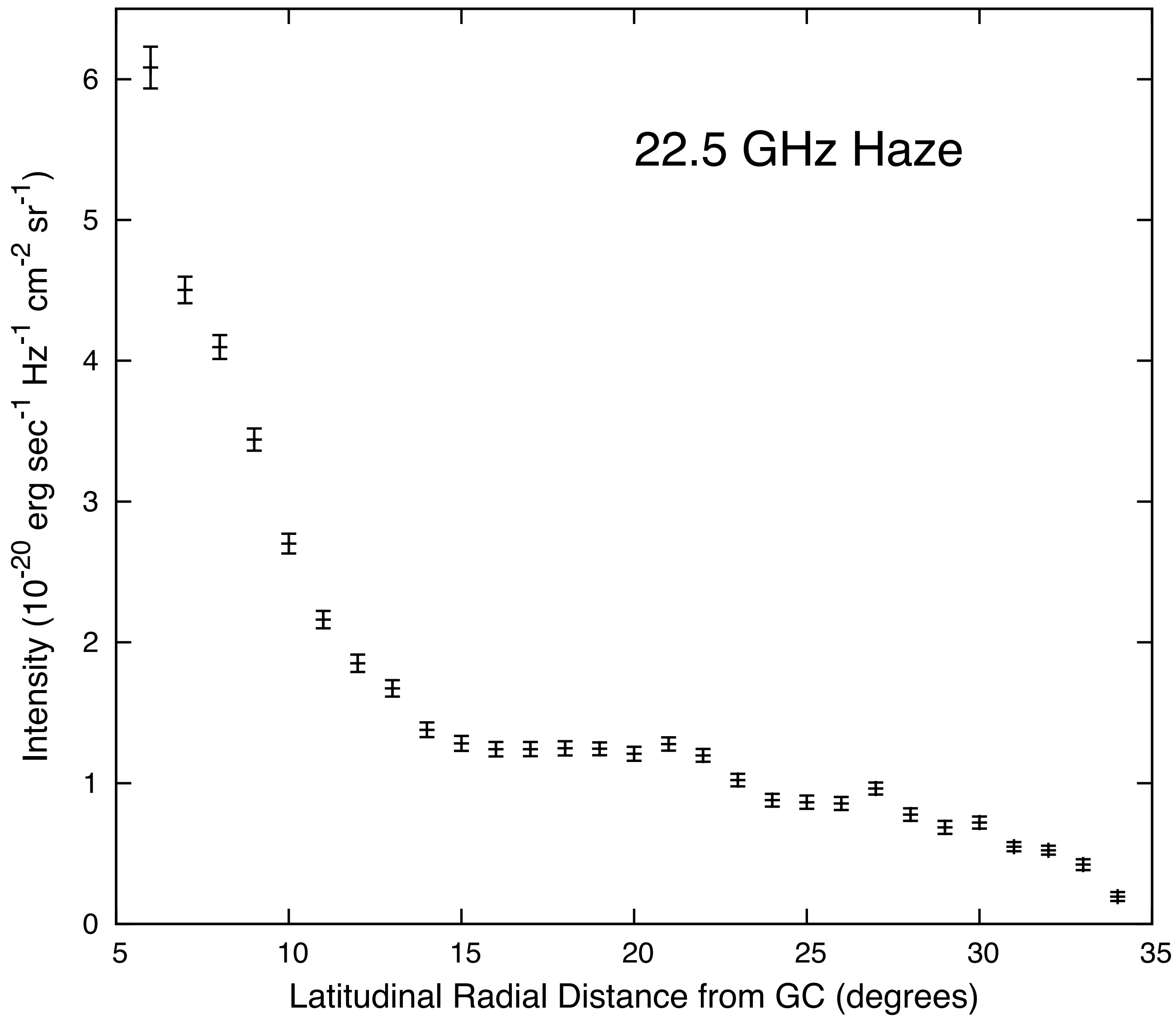


22.5 GHz

WMAP "Haze"

Finkbeiner astro-ph/0311547
Finkbeiner, Dobler arXiv:0712:1038

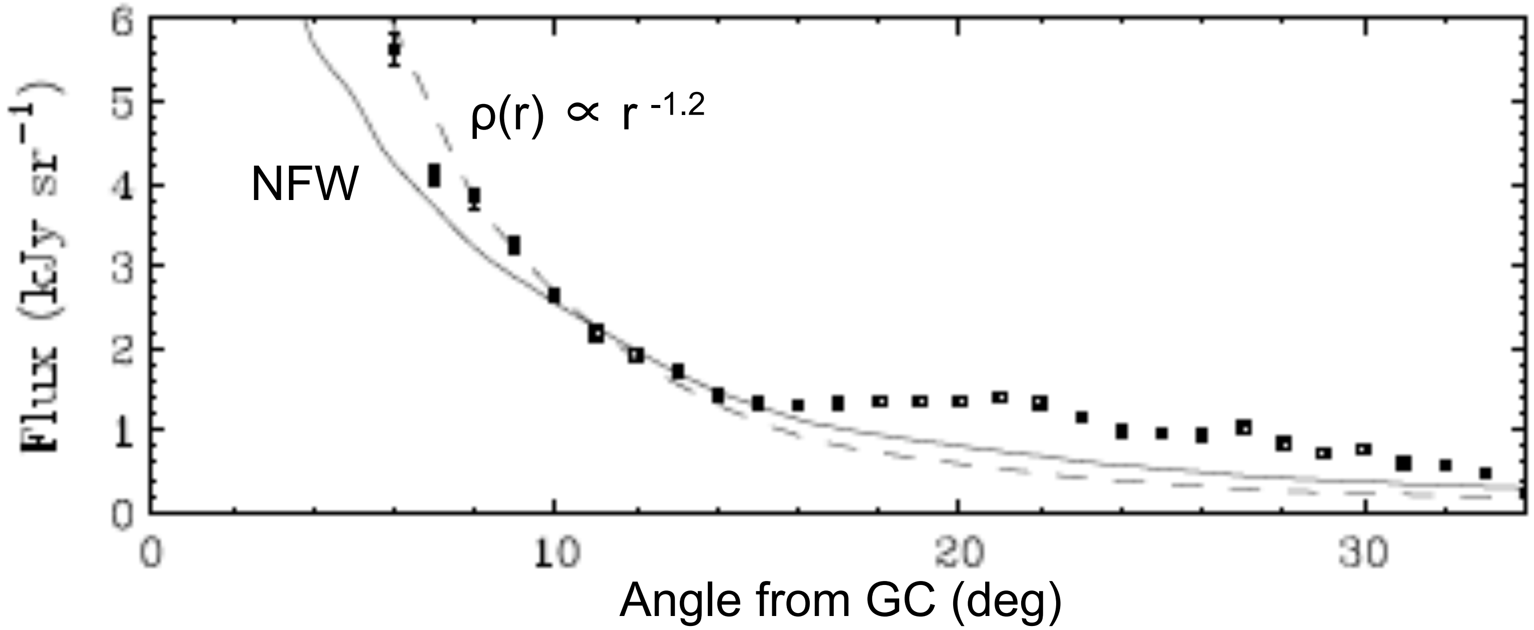
- Additional emission not correlated with known foregrounds
- Distributed with approximate radial symmetry within ~20° of GC and falls rapidly with distance from GC
- Spectrally consistent with hard synchrotron



There is an unknown source of high energy $e^+ e^-$ in the center of the Galaxy

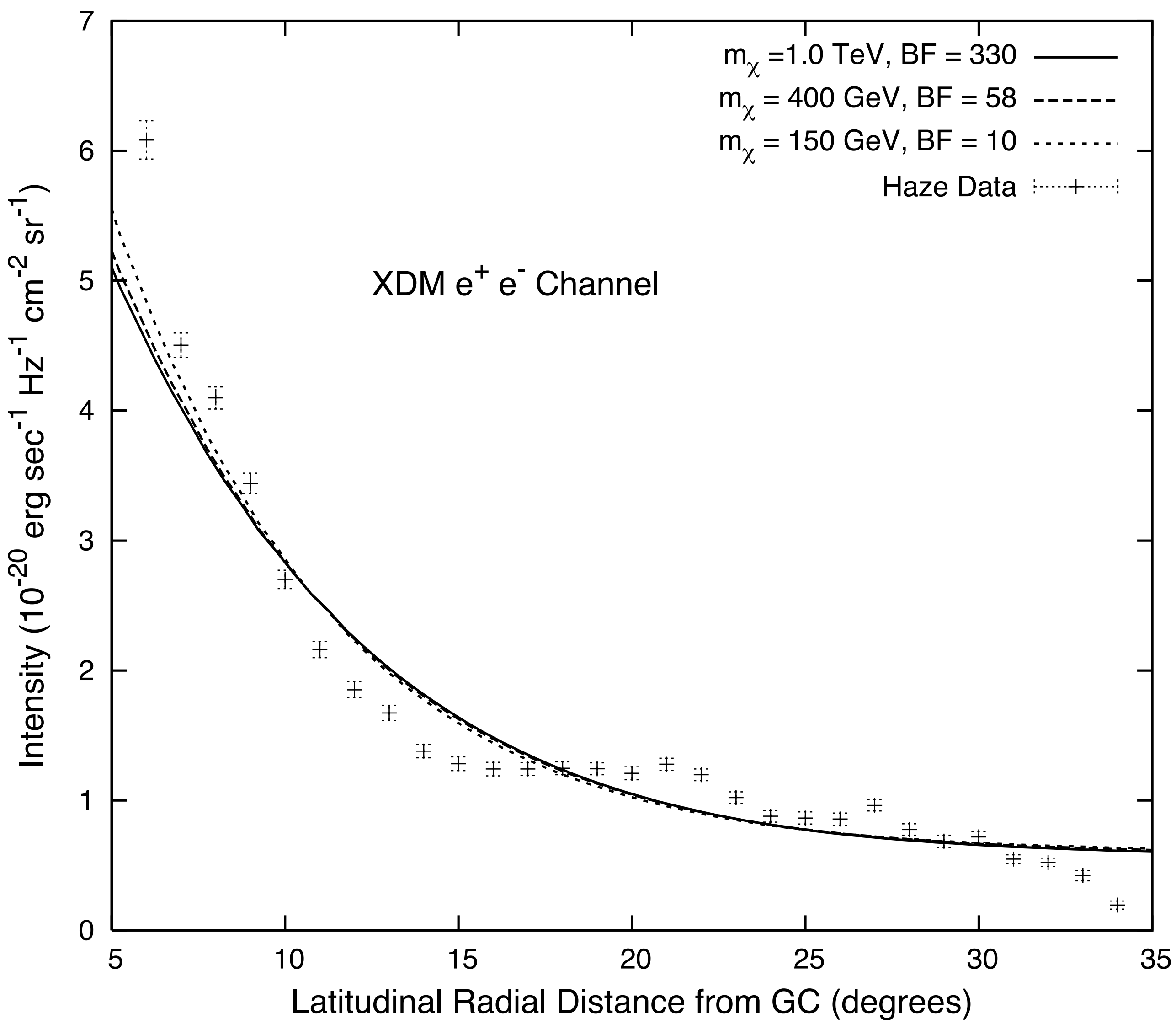
WMAP "Haze"

- Finkbeiner proposed that the Haze could be due to high energy $e^+ e^-$ coming from DM annihilations
- Hooper *et al* (2007), Cholis, LG and Weiner (2008) confirmed that this explanation is valid
- It is unlikely that the high energy $e^+ e^-$ are coming from standard astrophysical sources



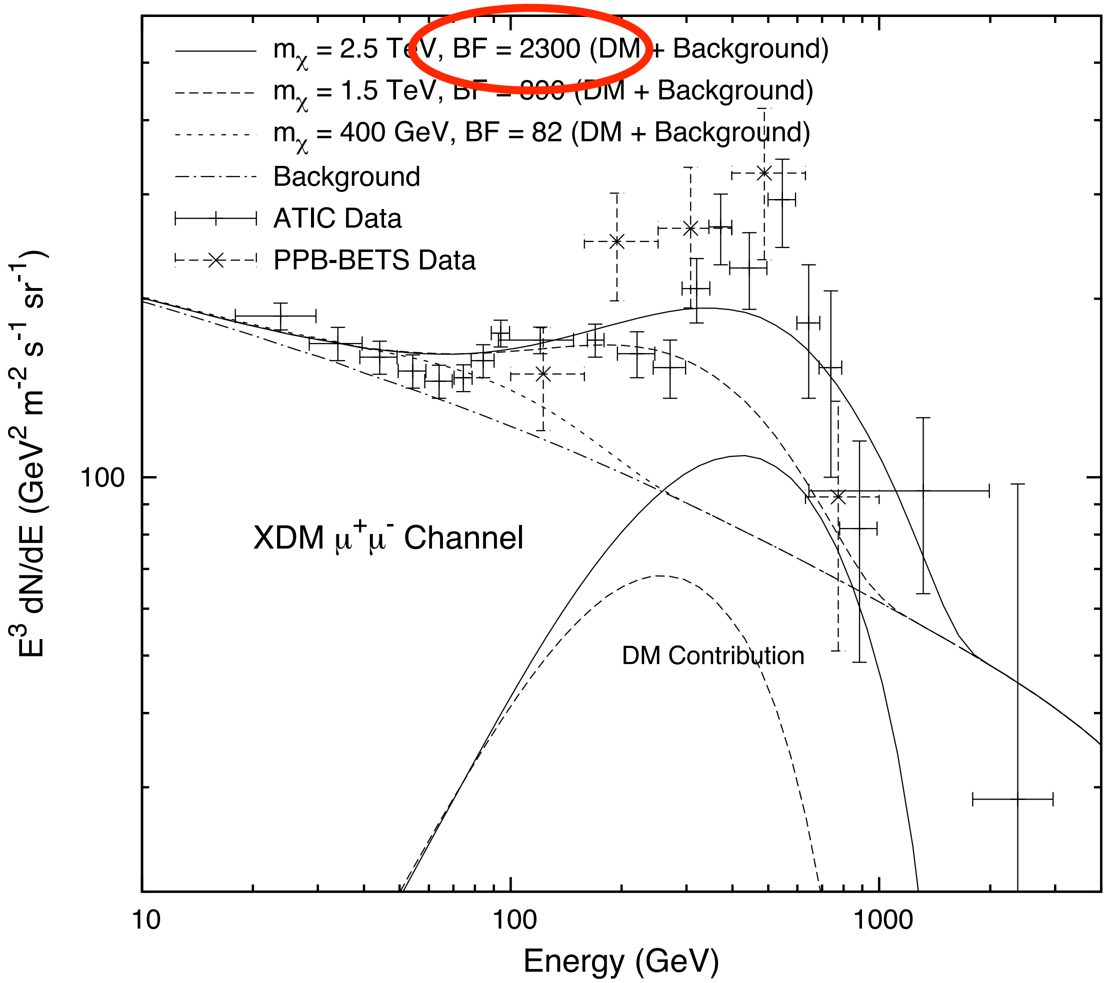
Hooper, Finkbeiner, Dobler arXiv:0705:3655

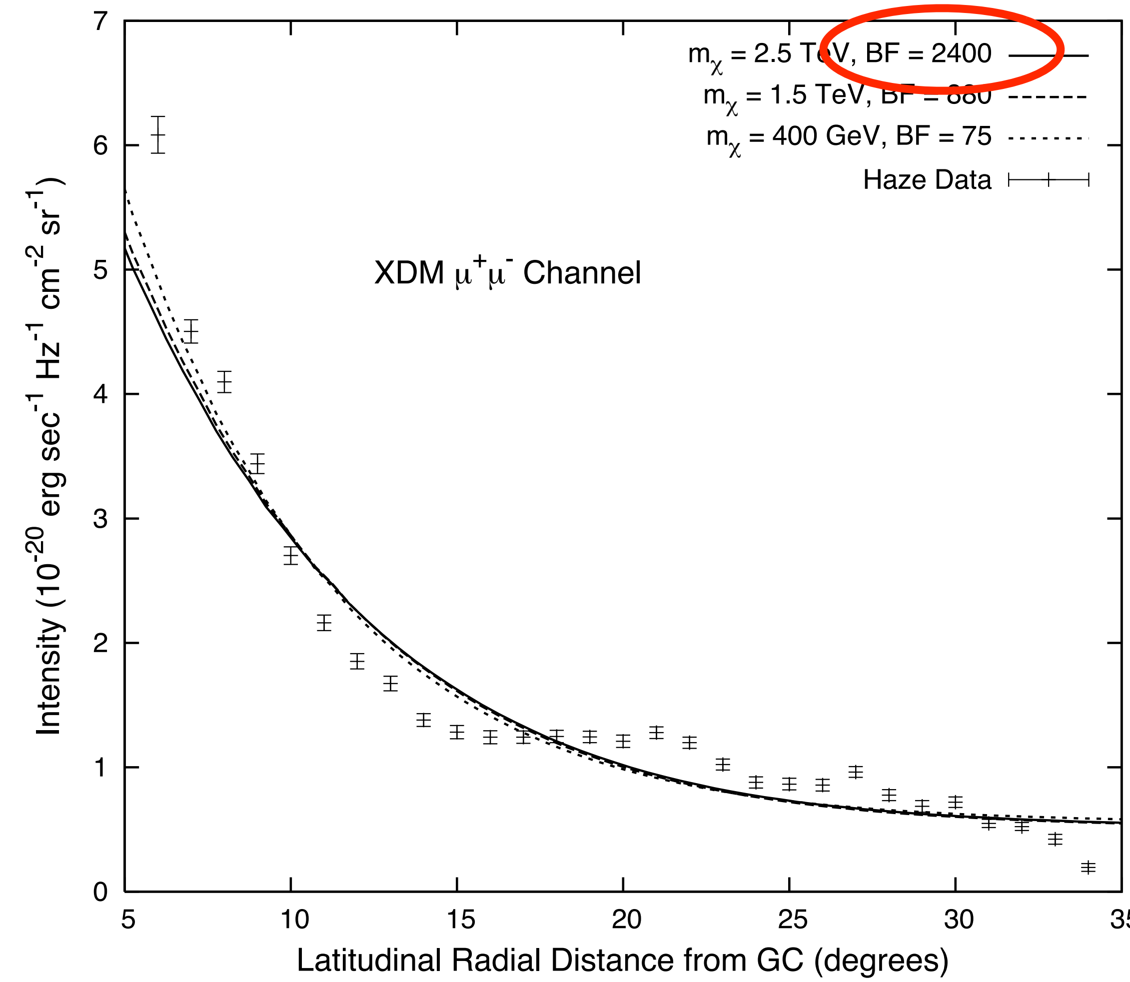
WMAP “Haze”

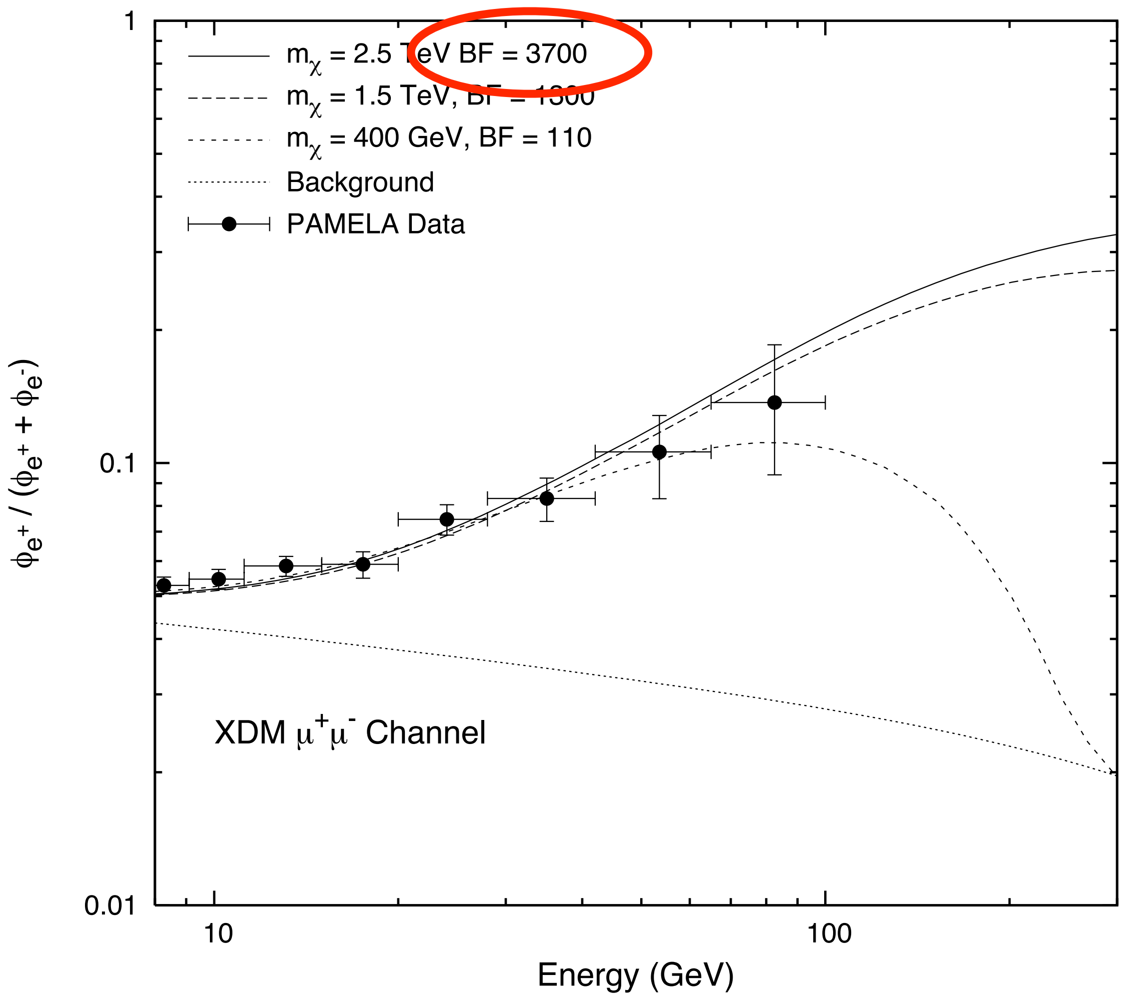


Cholis, Dobler, Finkbeiner, LG, Weiner arXiv:0811.3641

The same annihilation channels into charged leptons, directly or through a light mediator, that gave good fits to ATIC and PAMELA give good fits to the Haze







Boost factors needed to fit ATIC, PAMELA, and the Haze are comparable

- We have evidence for a population of e^+ e^- from DM annihilation in the center of the Galaxy
- Energies of these particles span the range between ~10 GeV and more than 100 GeV
- Electrons with these energies can Inverse Compton Scatter (ICS) lower energy optical photons
- These could be visible in the center of the Galaxy where the DM density is high

What energies do these ICS photons have?

$$\mathrm{E}_{upscatter} = 2E_{initial}\gamma^2$$

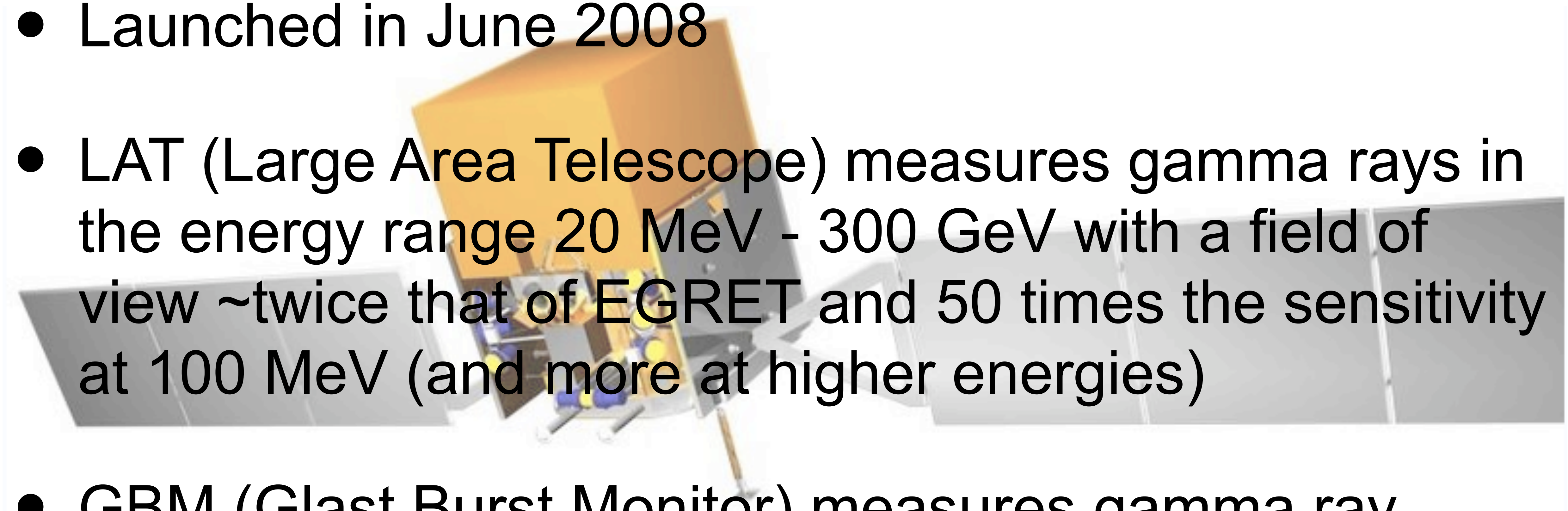
For optical photons with energies ~ eV and electrons with energies of 100 GeV, the upscattered photon will have an energy of 80 GeV

EGRET has measured gamma rays, but not with any accuracy above ~10 GeV, however

This is precisely in the energy range of Fermi/GLAST

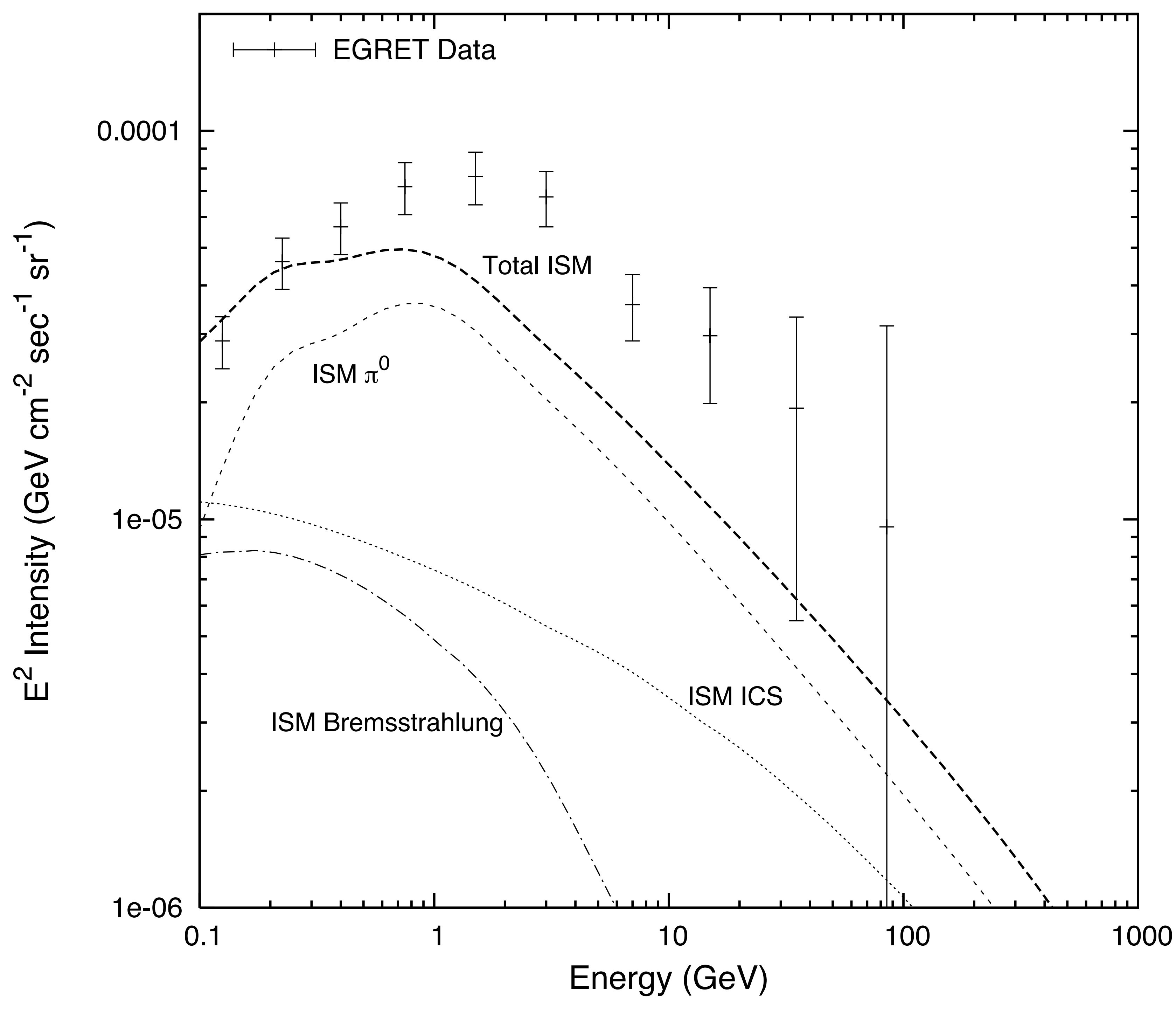
Fermi

Gamma-ray Space Telescope

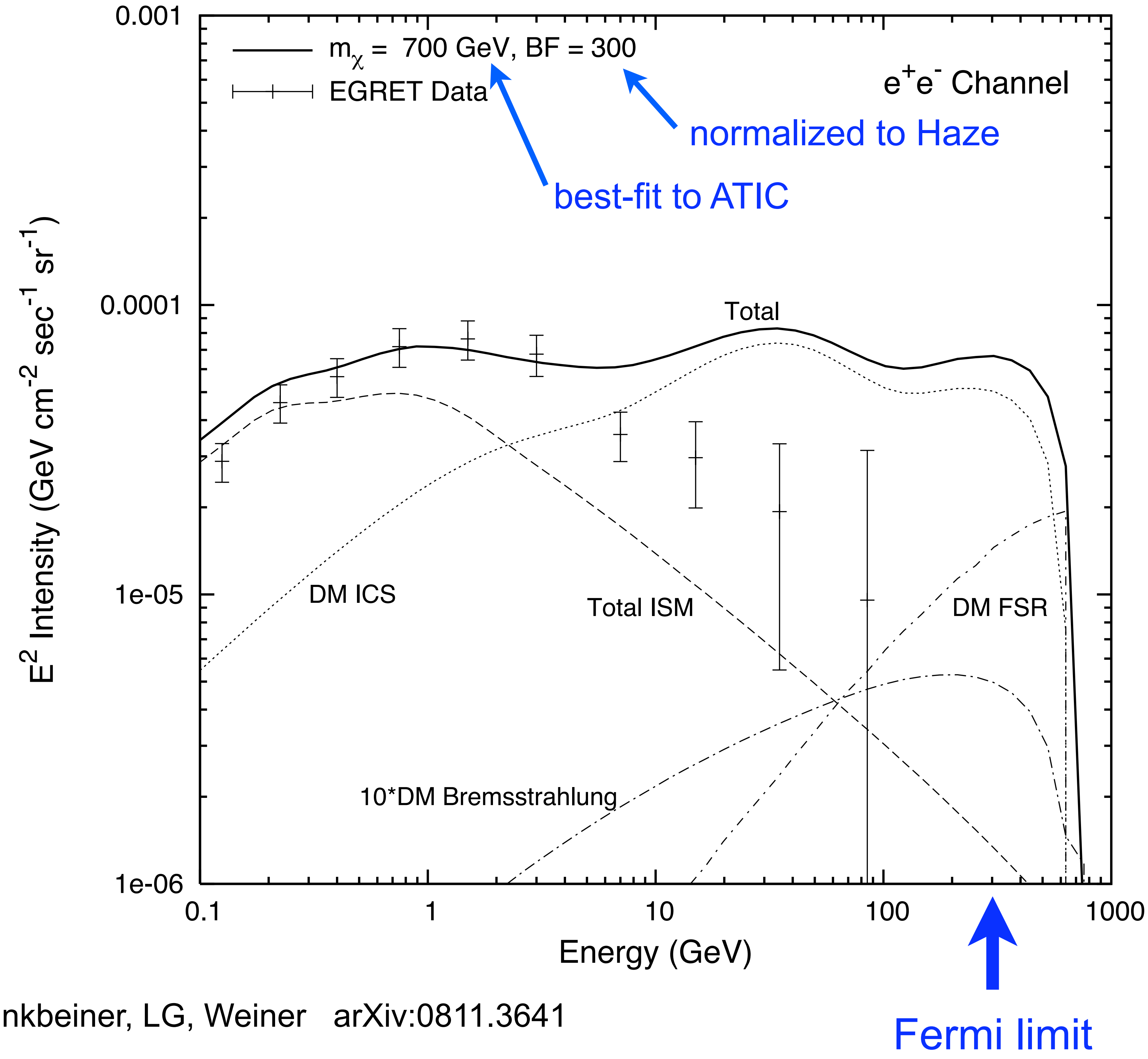


- Launched in June 2008
- LAT (Large Area Telescope) measures gamma rays in the energy range 20 MeV - 300 GeV with a field of view ~twice that of EGRET and 50 times the sensitivity at 100 MeV (and more at higher energies)
- GBM (Glast Burst Monitor) measures gamma ray bursts in energy range 8 keV - 25 MeV

Background Gamma Ray Flux



Gamma Ray Flux $\chi\,\chi \longrightarrow e^+e^-$



Cholis, Dobler, Finkbeiner, LG, Weiner arXiv:0811.3641

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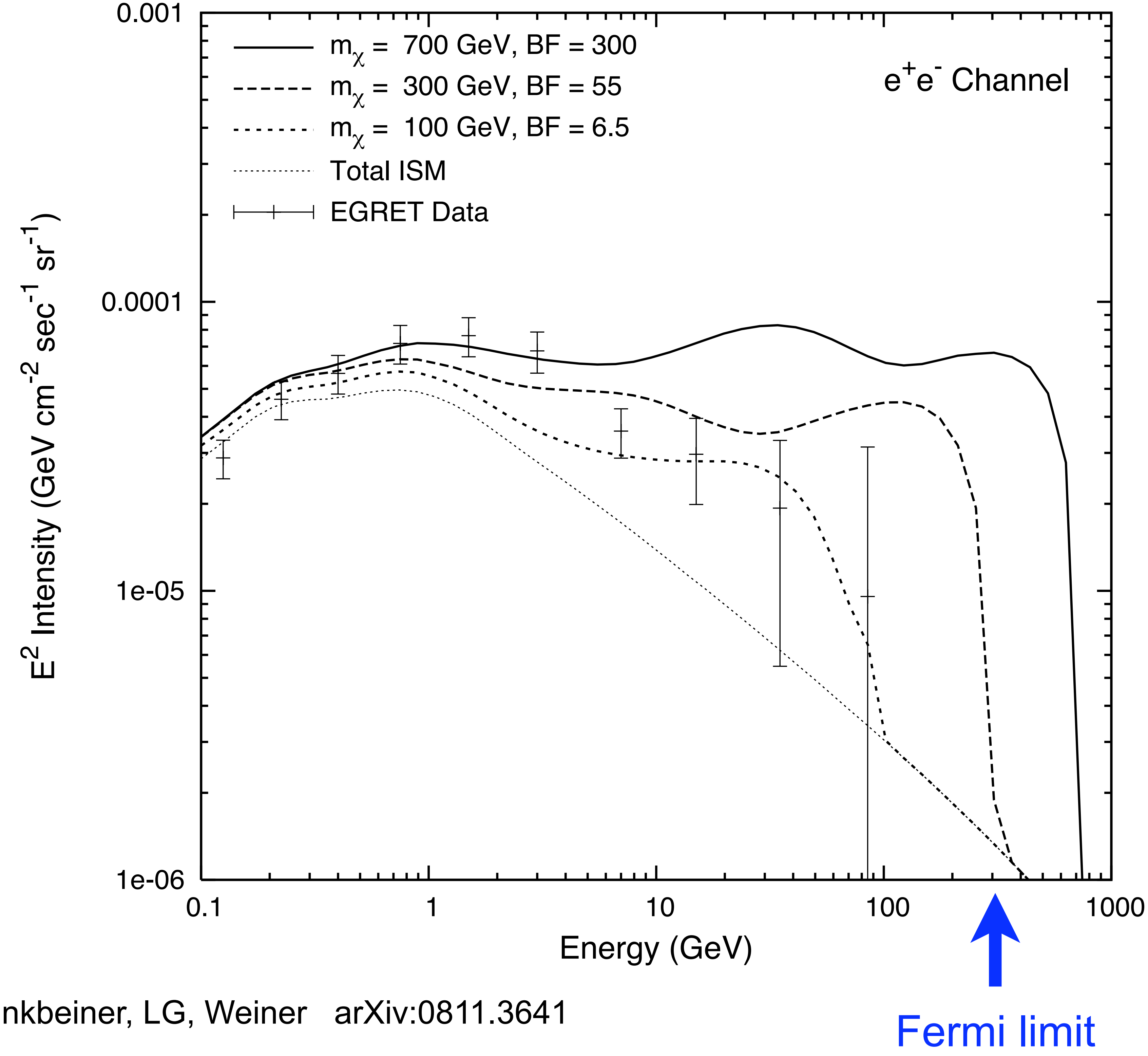

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Uncertainties in Gamma Ray Flux

Annihilation rate in the center of the Galaxy may be different from that at our galactic position

We normalize the annihilation rate to that of the Haze, the signal from the Galactic Center

Magnetic field in the center of the Galaxy is not well known

We estimate the uncertainties in the boosts for the Haze to be ~2

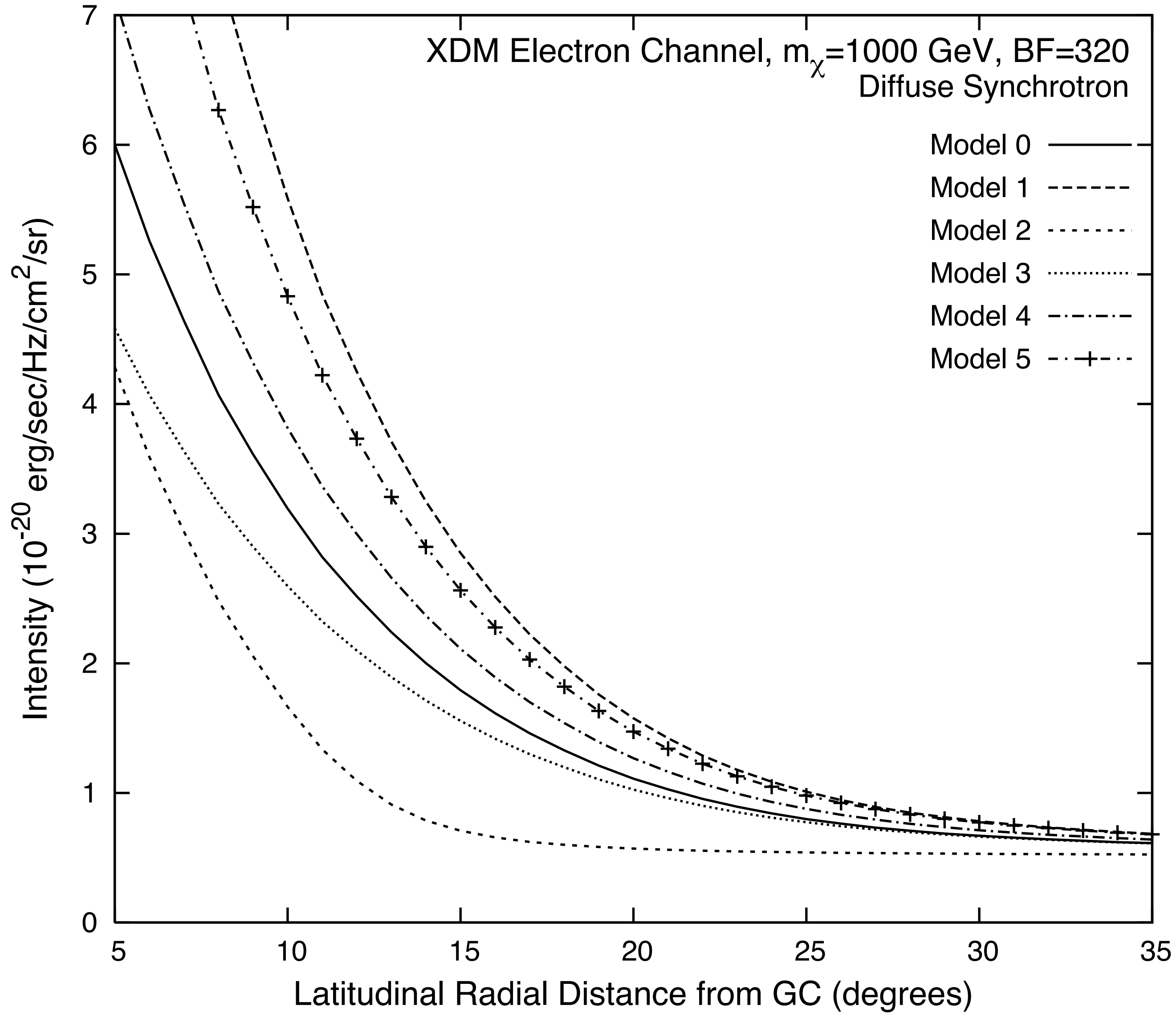
There is some uncertainty in the ISRF

A decrease in the ISRF would result in less power to ICS and more power to synchrotron resulting in an over-estimation of the ICS signal

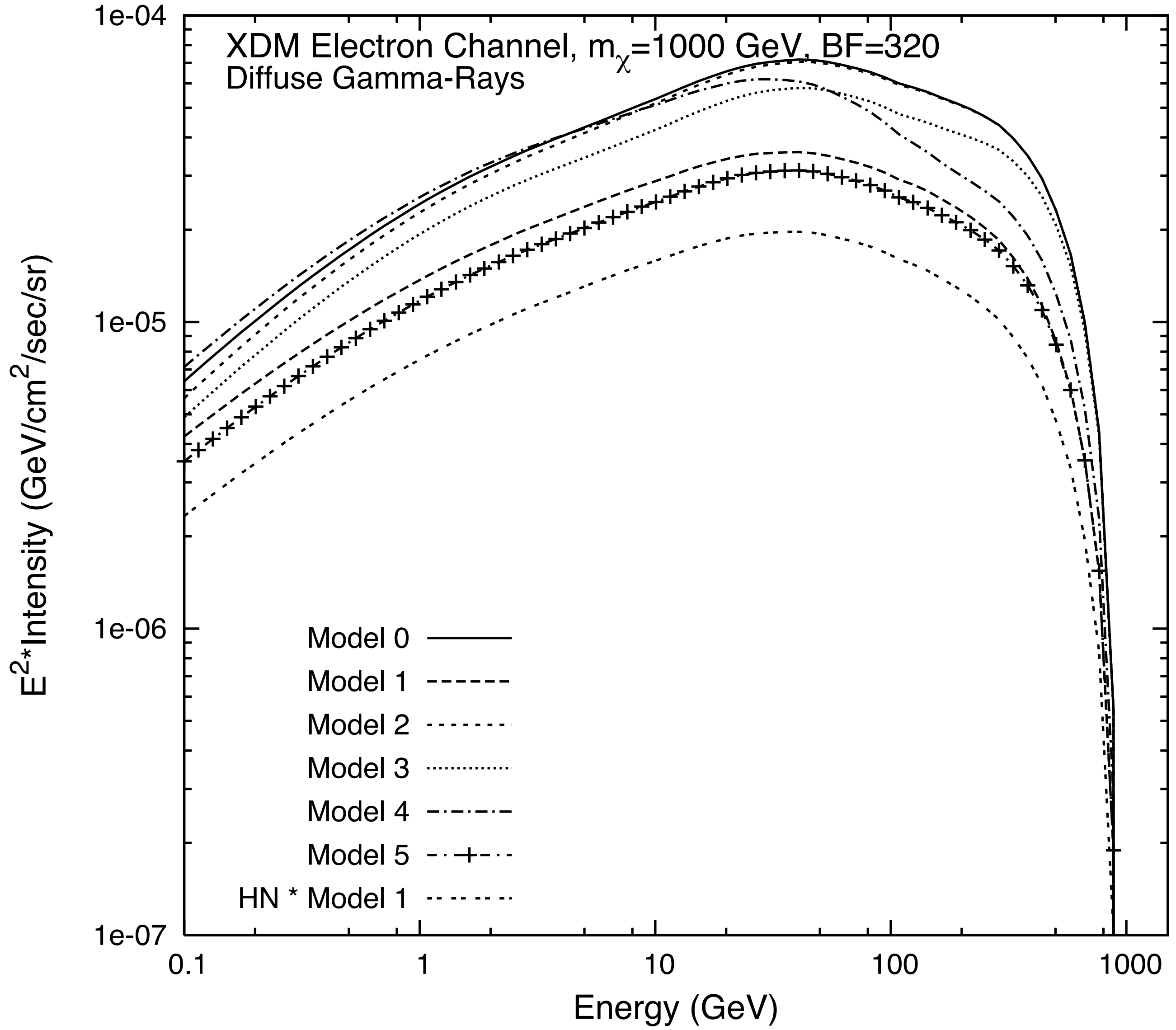
There is some uncertainty in the diffusion parameters

An increase in the diffusion coefficient would result in less ICS and less synchrotron, as the electrons don’t spend as much time in the center of the Galaxy

DM Synchrotron



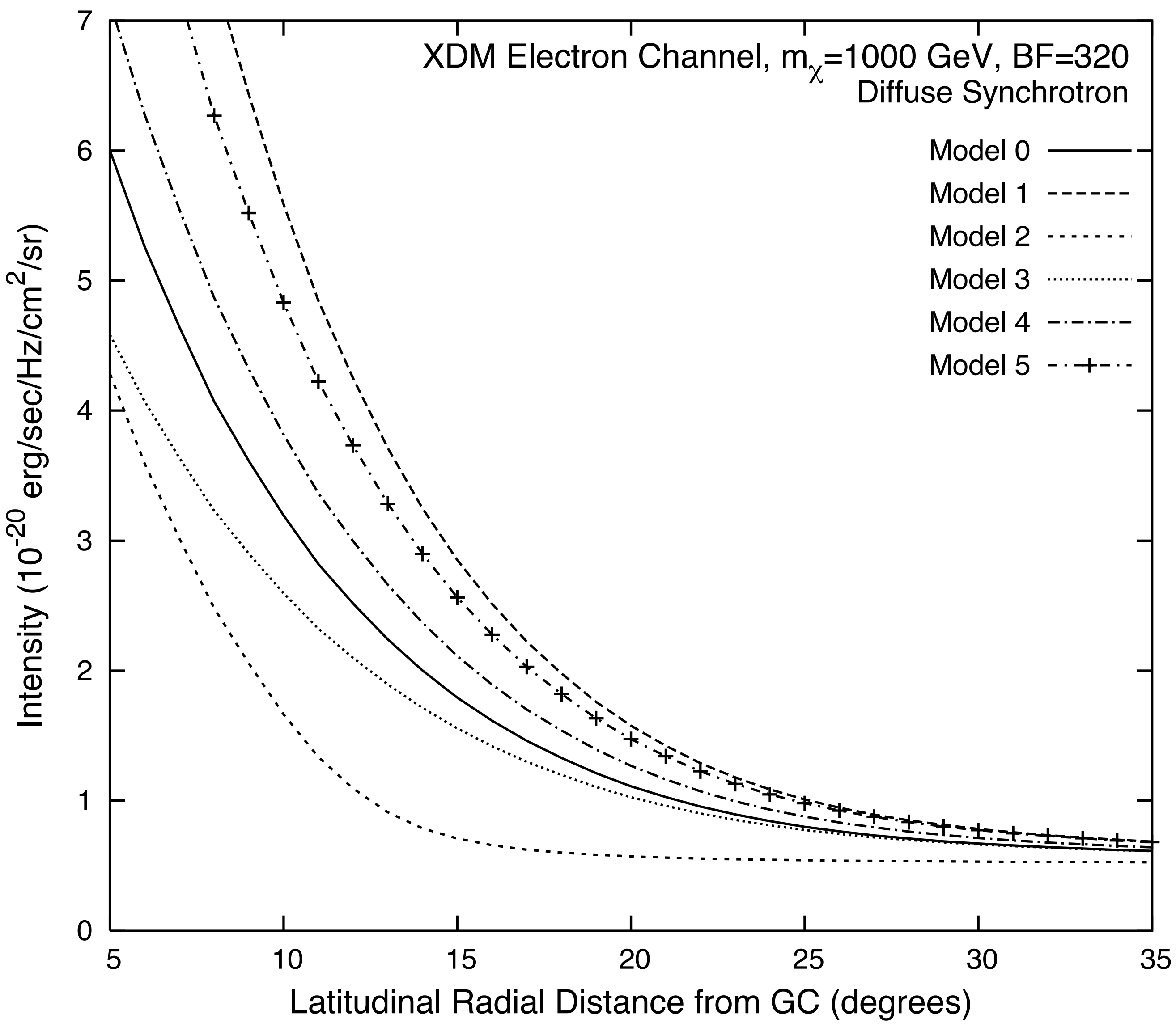
DM ICS



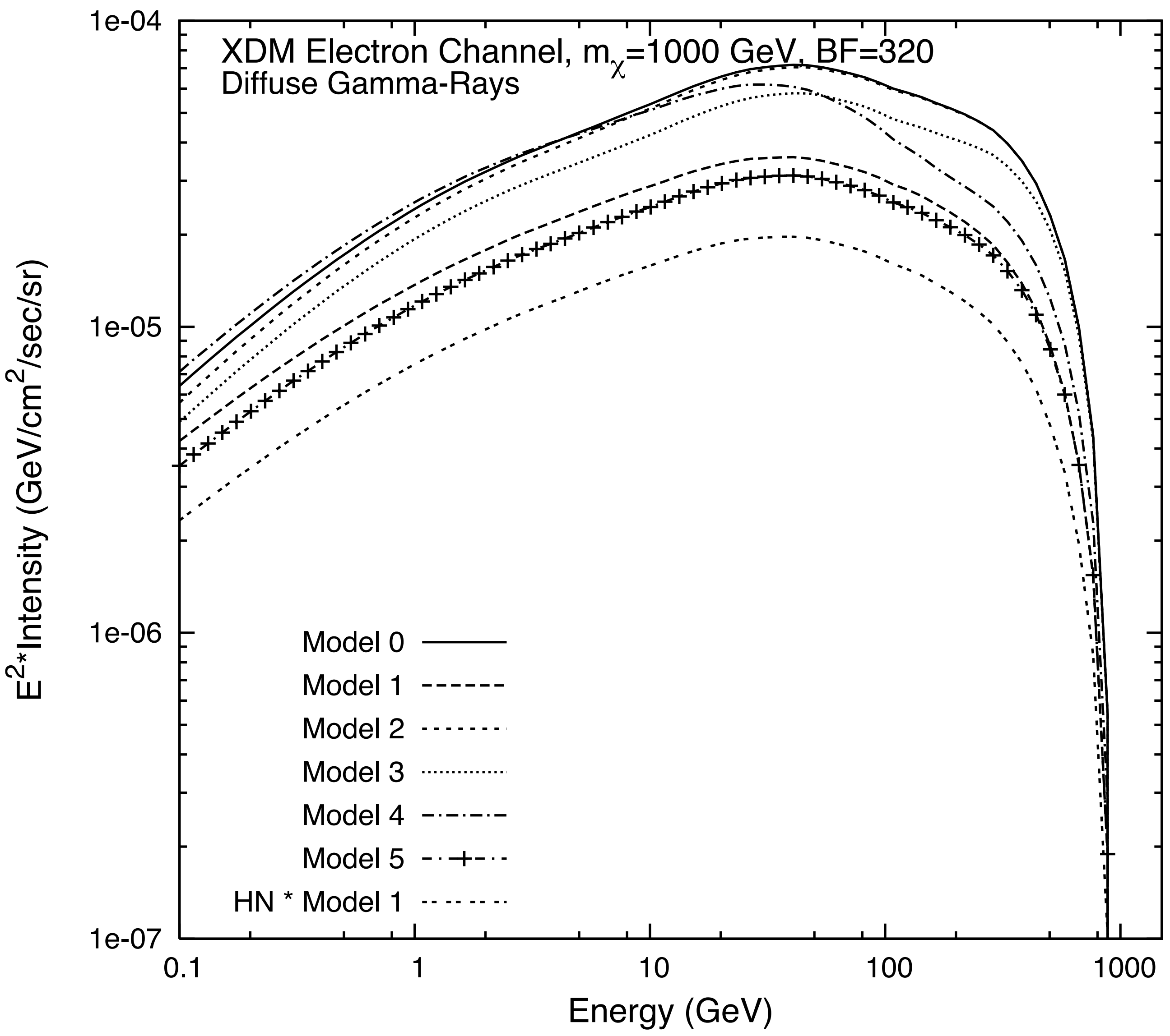
Model 0: Benchmark model

Model 1: Magnetic Field is doubled

DM Synchrotron



DM ICS

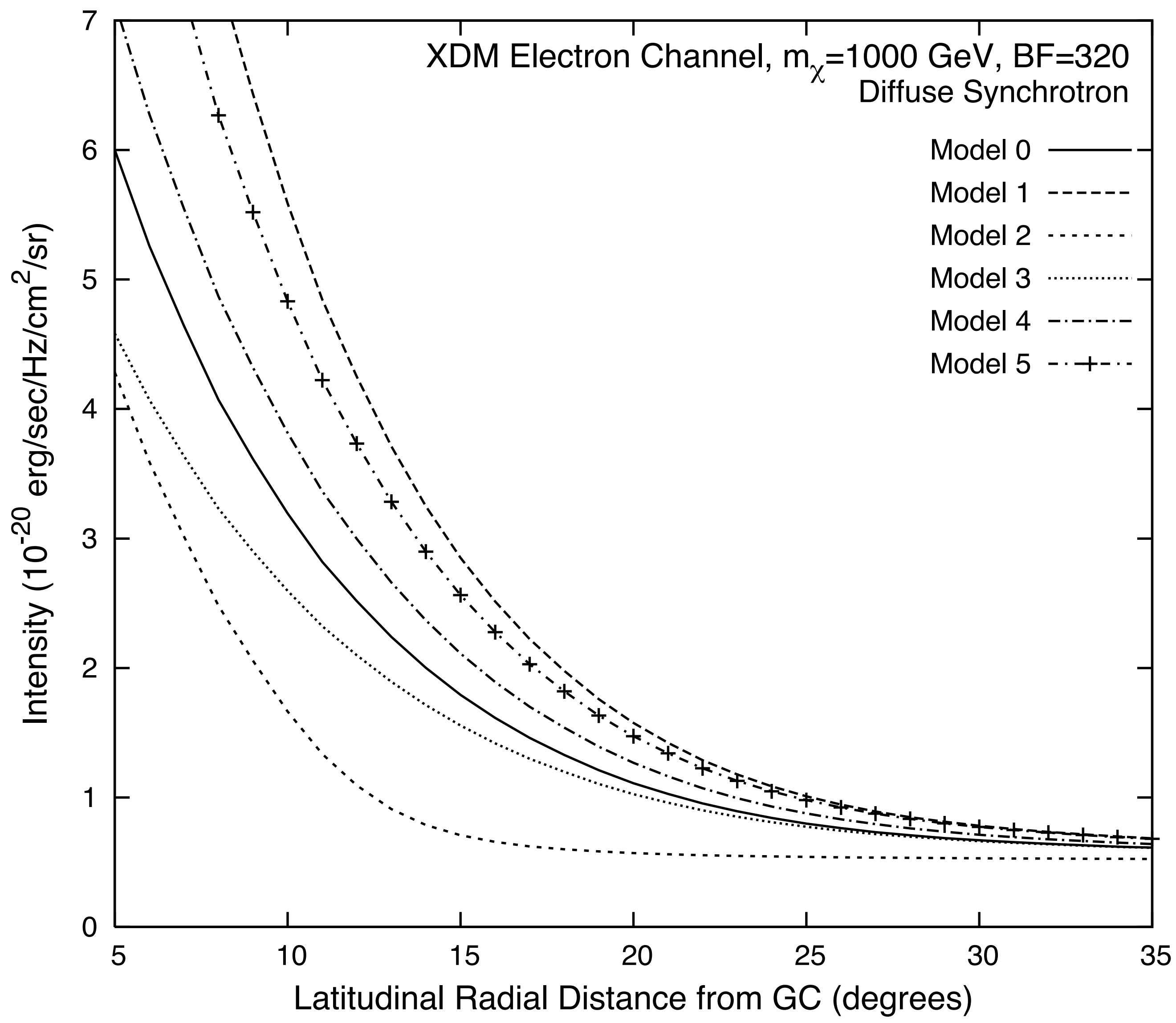


Model 0: Benchmark model

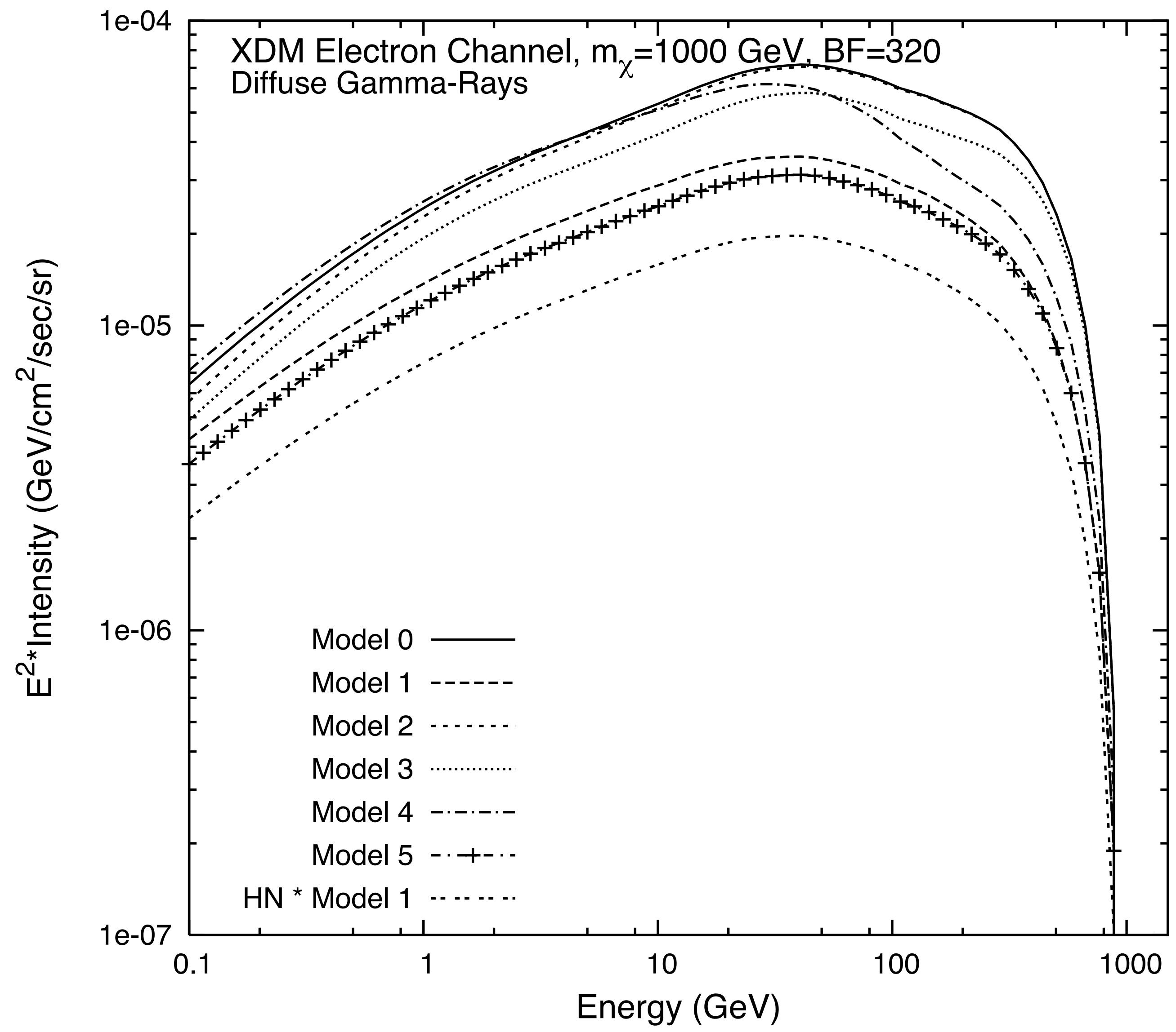
Model 1: Magnetic Field is doubled

Model 2: Diffusion zone reduced from z = 4 kpc to z = 2 kpc

DM Synchrotron

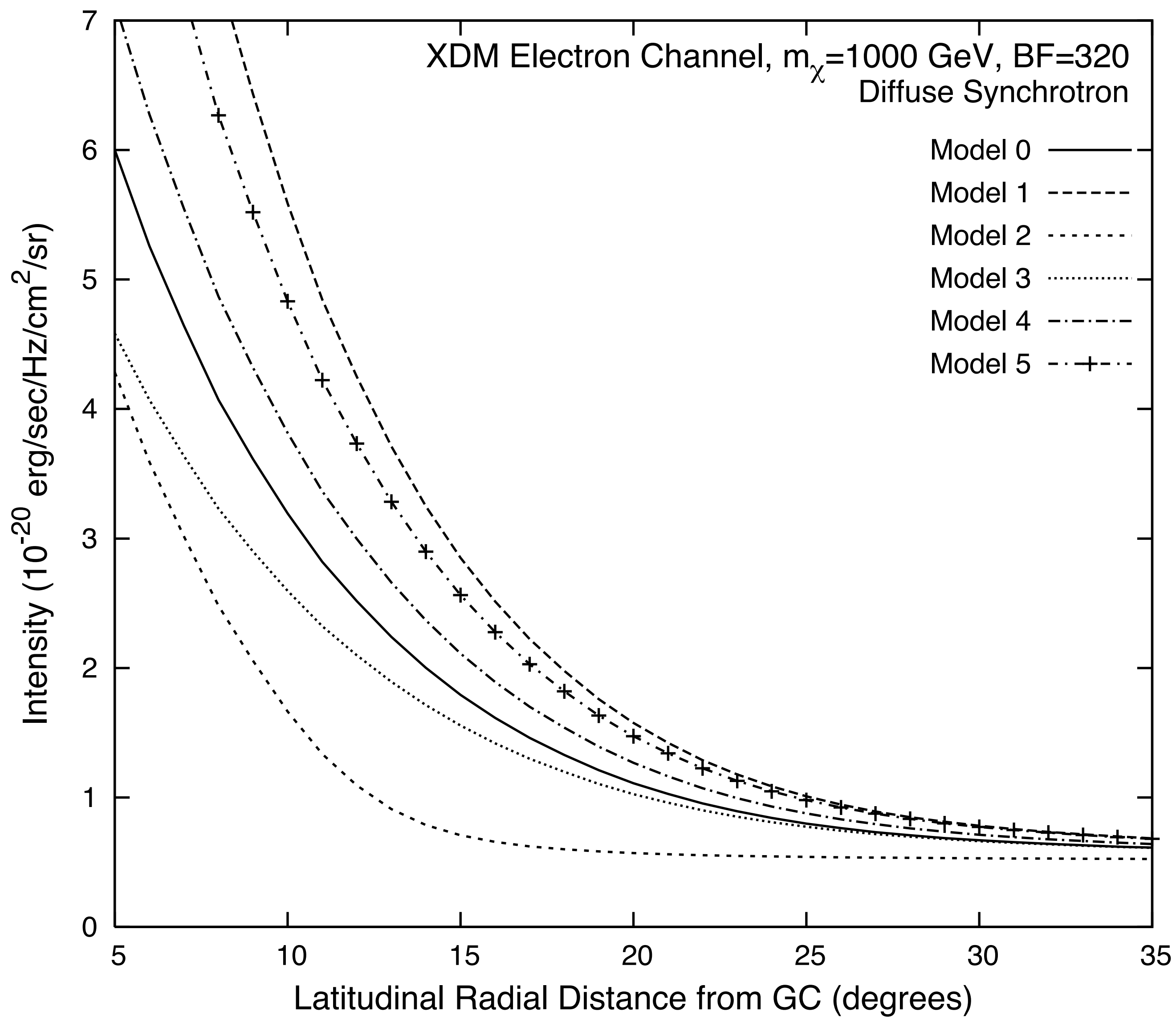


DM ICS

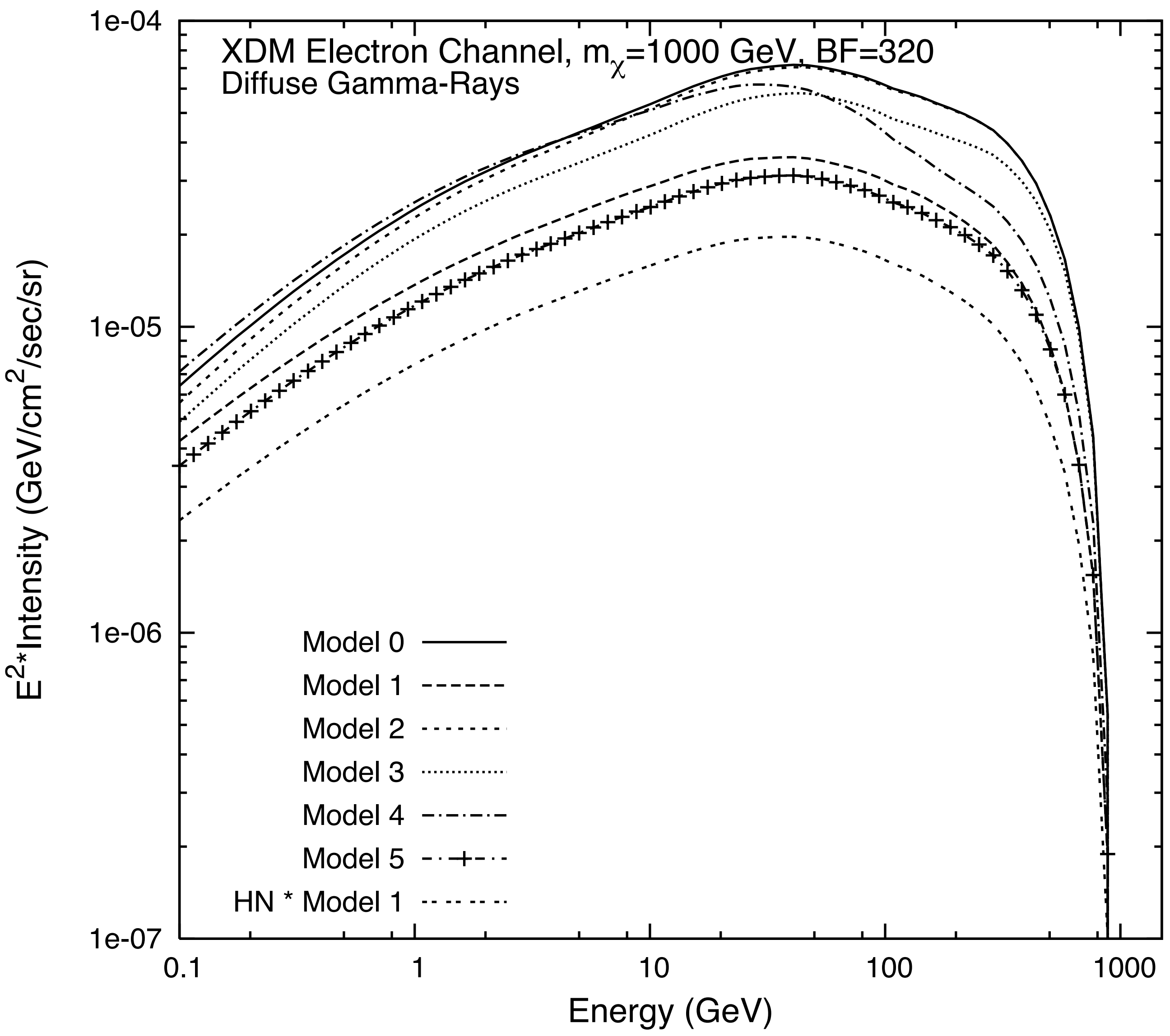


Model 0: Benchmark model
Model 1: Magnetic Field is doubled
Model 2: Diffusion zone reduced from z = 4 kpc to z = 2 kpc
Model 3: Diffusion index changed from 0.33 to 0.50

DM Synchrotron

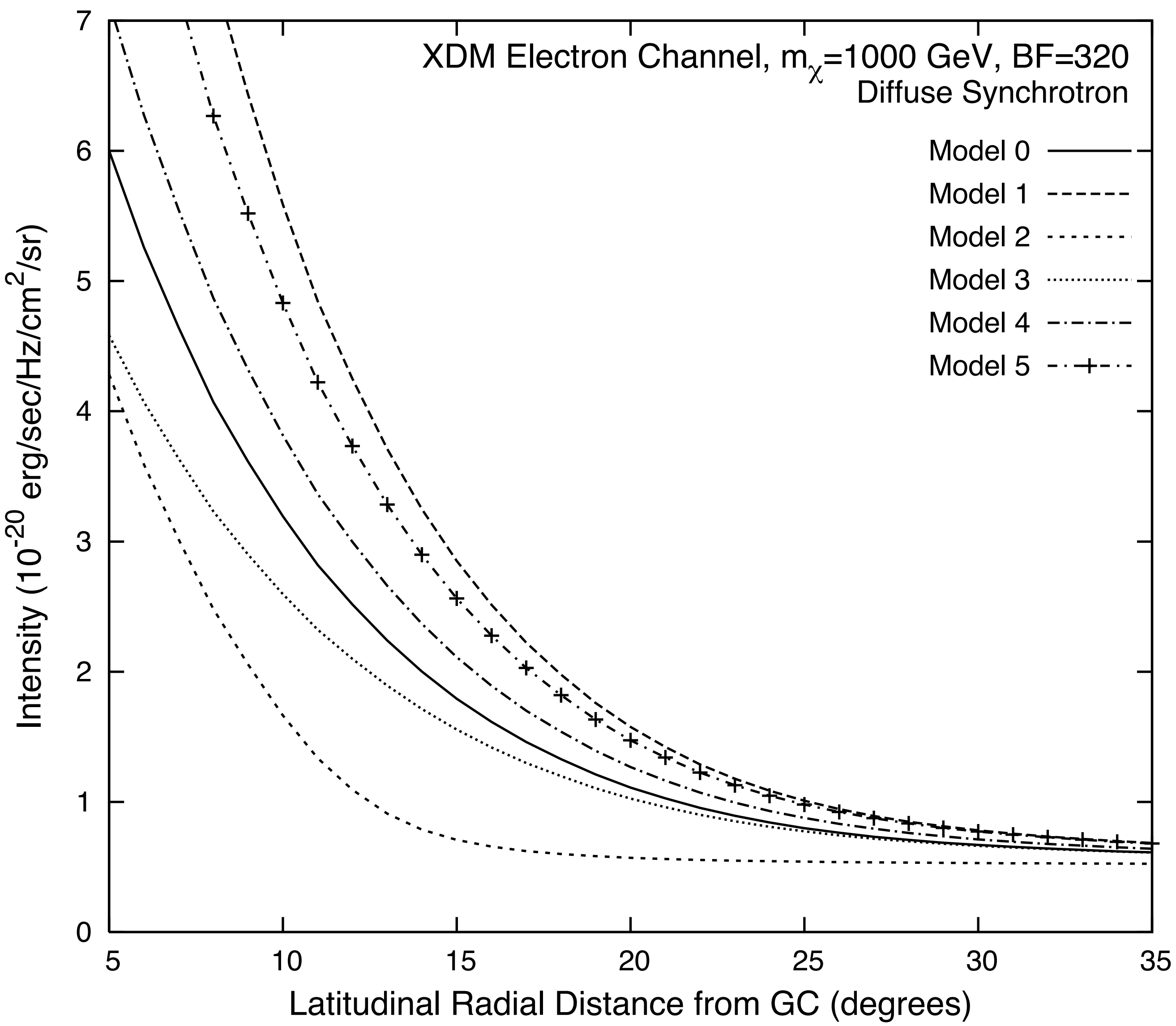


DM ICS

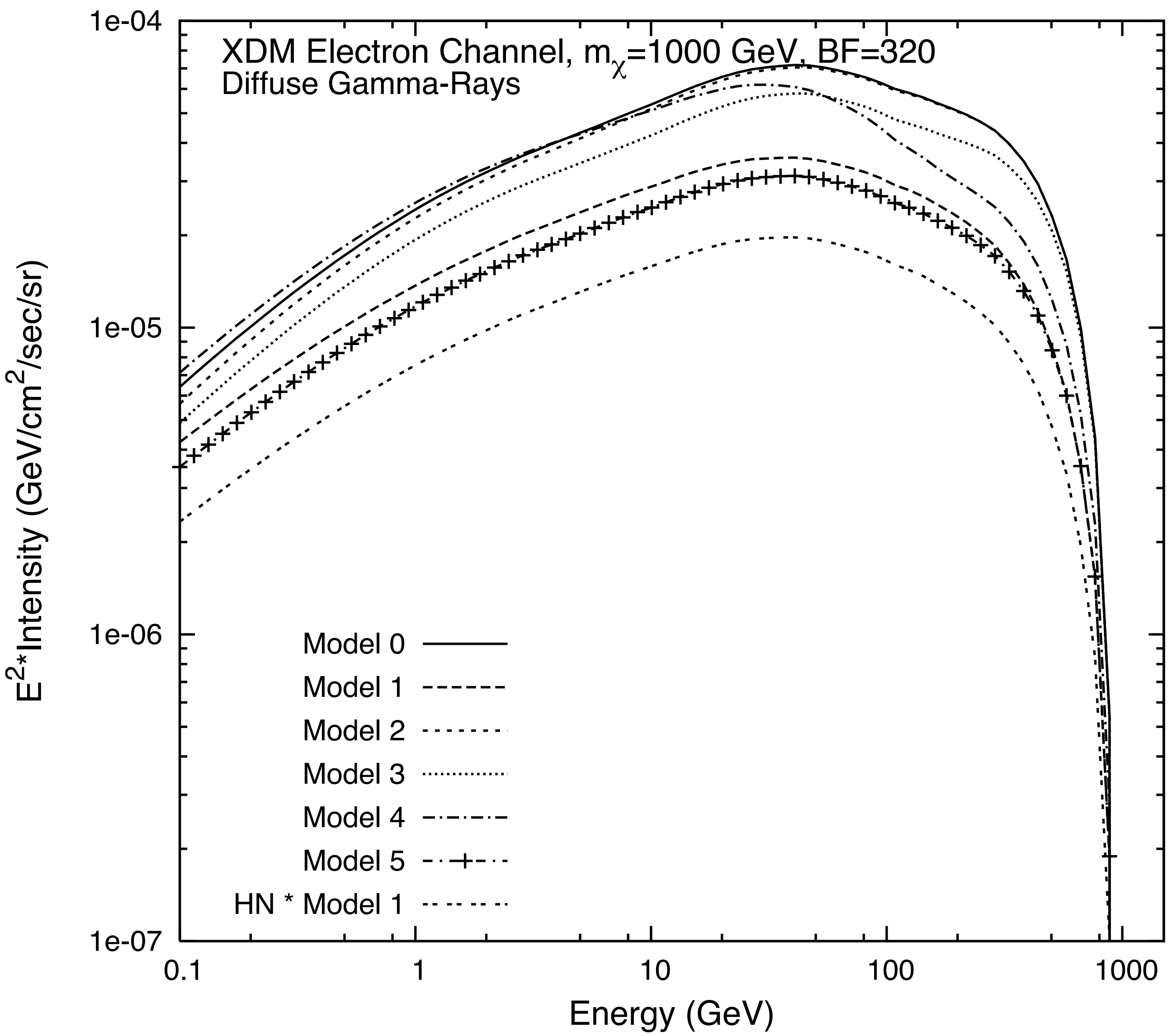


Model 0: Benchmark model
Model 1: Magnetic Field is doubled
Model 2: Diffusion zone reduced from z = 4 kpc to z = 2 kpc
Model 3: Diffusion index changed from 0.33 to 0.50
Model 4: Energy density in optical wavelengths of ISRF reduced by 1/2

DM Synchrotron

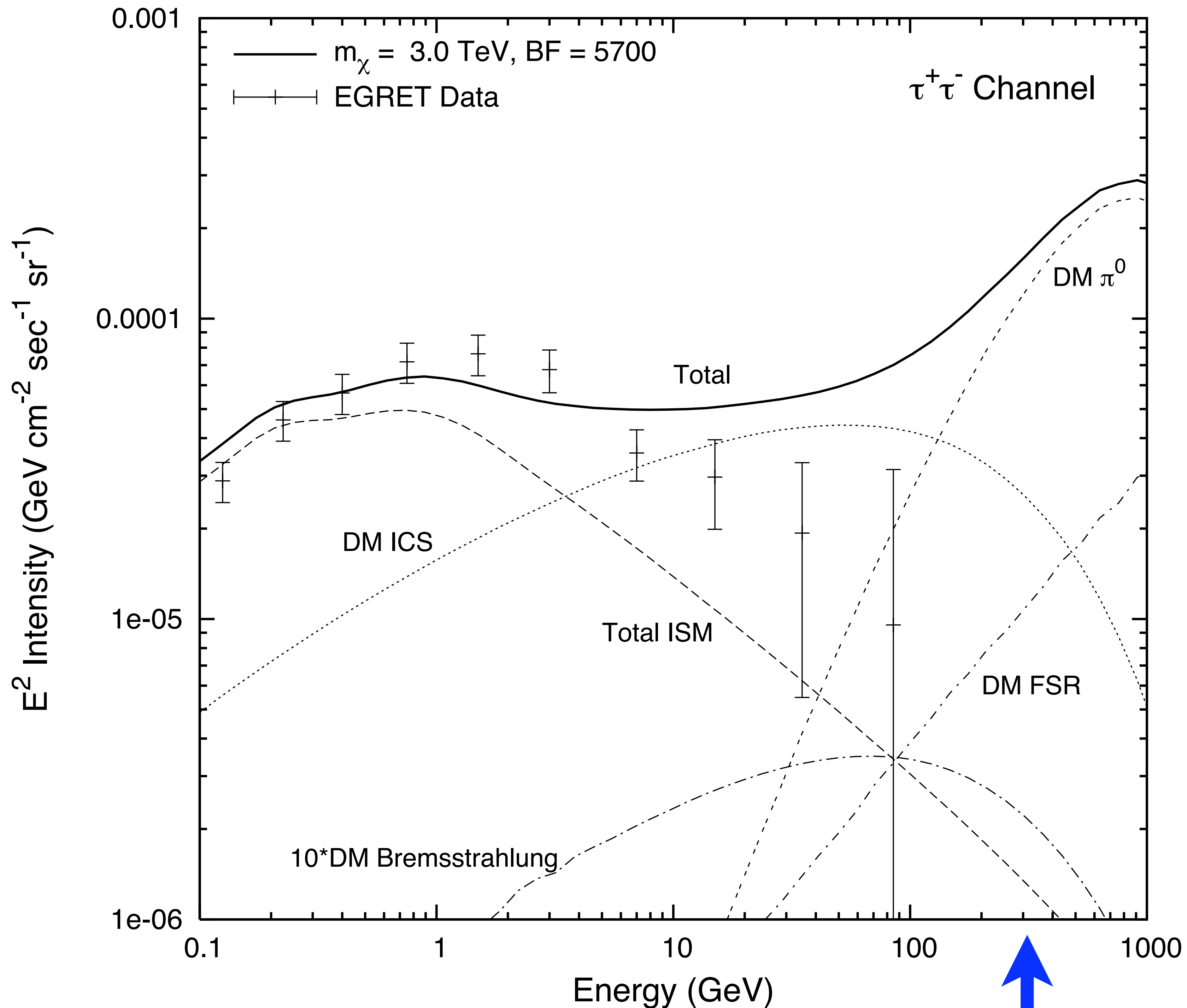


DM ICS



Model 0: Benchmark model
Model 1: Magnetic Field is doubled
Model 2: Diffusion zone reduced from z = 4 kpc to z = 2 kpc
Model 3: Diffusion index changed from 0.33 to 0.50
Model 4: Energy density in optical wavelengths of ISRF reduced by 1/2
Model 5: Magnetic Field doubled and diffusion index changed from 0.33 to 0.50

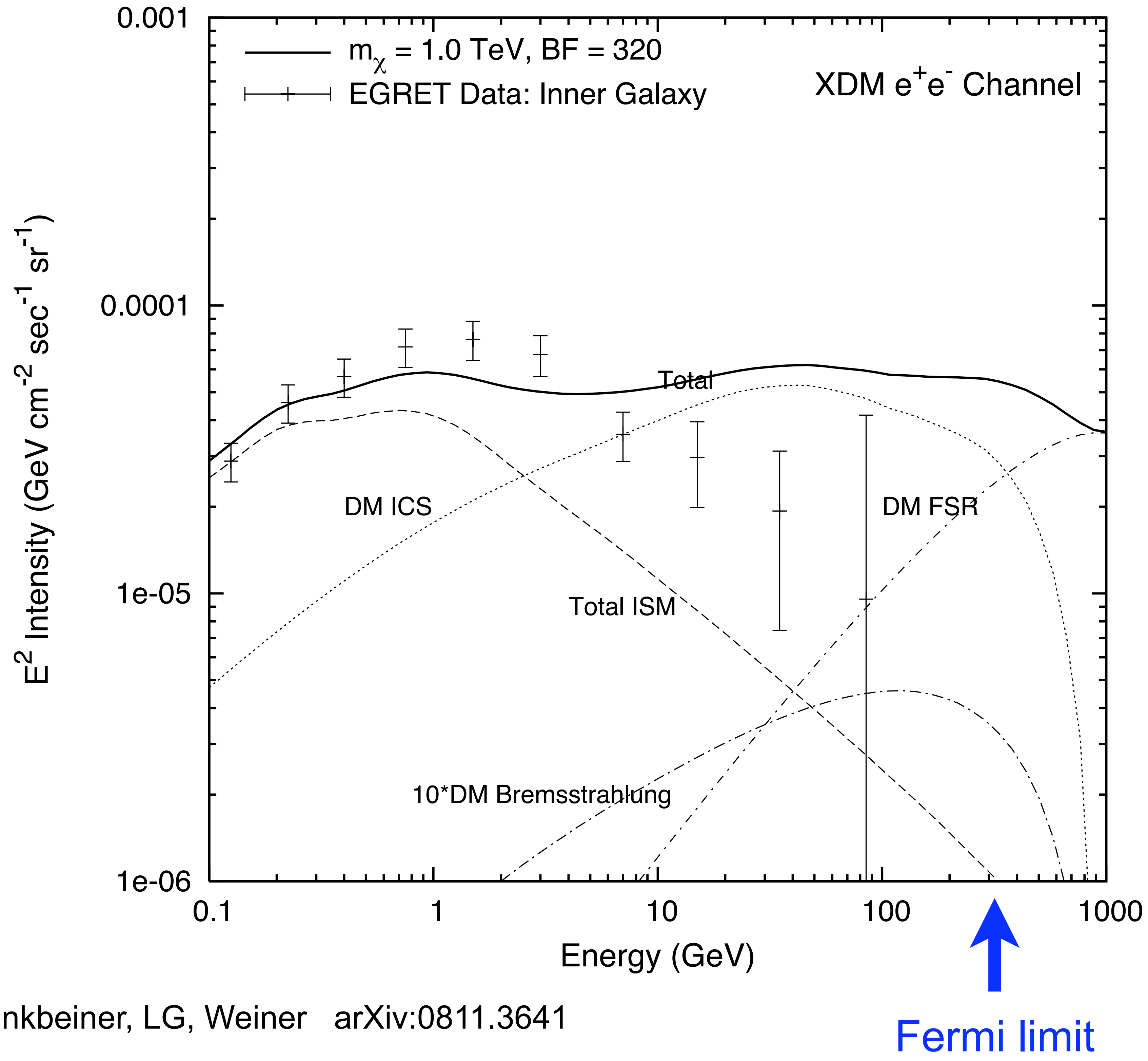
Gamma Ray Flux $\chi\,\chi \longrightarrow \tau^+\tau^-$



Cholis, Dobler, Finkbeiner, LG, Weiner arXiv:0811.3641

Fermi limit

Gamma Ray Flux $\quad \chi\,\chi \longrightarrow \phi\,\phi \longrightarrow e^+e^-$



Cholis, Dobler, Finkbeiner, LG, Weiner arXiv:0811.3641

In summary

- ATIC and PAMELA indicate an excess of local e^+ e^- with energies ~10 GeV to more than 500 GeV
- The WMAP Haze indicates an excess of e^+ e^- with comparable energies in the Galactic Center
- These excesses can be explained in terms of DM annihilating dominantly into leptons, either directly or through a light mediator (XDM scenario)
- Similar, though large, annihilation rates are required to explain all three measurements
- The excess population of e^+ e^- will contribute to the gamma ray signal in the energy range above 10 GeV, which may be observable by Fermi